STUDIES OF SLAG CARRY-OVER DURING DRAINAGE OF METALLURGICAL VESSELS

BY

P. UMAKANTH

DEPARTMENT OF METALLURGICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

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STUDIES OF SLAG CARRY - OVER DURING DRAINAGE OF METALLURGICAL VESSELS

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BY

P. UMAKANTH

to the

DEPARTMENT OF METALLURGICAL ENGINEERING

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APRIL, 1992

CERTIFICATE

This is to certify that the work entitled 'STUDIES OF SL CARRY-OVER DURING DRAINAGE OF METALLURGICAL VESSELS' is the reco of the work carried out by UMA KANTH under my supervision and h not been submitted elsewhere for the award of a degree.

Dr. S. C. Koria
Assistant Professor

Department of Metallurgical Engineering
Indian Institute of Technology
Kanpur

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NOMENCLATURE

A_n = Cross Sectional Area of Nozzle

A_V = Cross Sectional Area of Vessel

D = Diameter of Nozzle

f = Friction Factor

g = Acceleration due to Gravity

H_f = Final Water Height

H_V = Vortex Height

H_I = Initial Water Height

H = Water Height

m = Mass of Particle

Q_i = Inlet Flow Rate

Q_n = Flow Rate Through Nozzle

r = Radius

T_V = Vortex Time

T = Total Time to Empty the Vessel

t = Time

$\bar{U}$ = Average Velocity

V = Millivolts

WT = Waiting Time

ABSTRACT

In the present investigation the study of slag carry-over during drainage of metallurgical vessels is carried by a water model.

The effect of mode of filling, nozzle diameter, inlet flow rate, nozzle position and waiting time on the vortex formation height is studied.

Two electrical circuits, one for the continuous measurement of water level and the other for detection of the vortex are employed in this investigation.

The above study has been organized in the following chapters:

Chapter 1 describes the effect of slag carry-over due to vortex and Drain Sink formation. Literature review has been made about the information on slag carry-over during draining of metallurgical vessels because of the vortex and Drain Sink formation.

Chapter 2 describes about the experimental set-up, electrical circuits for the measurement of water level in the vessel and for the detection of vortex formation. The calibration of m.v. values in terms of water level, and experimental procedure have also been described in this chapter.

The experimental results are presented and discussed in Chapter 3. The effect of different variables i.e. nozzle diamter, mode of filling etc. on the vortex formation height and time have been discussed.

Correlations are developed to predict the vortex height and time. The calculated values of vortex height from the above correlations have been compared with the observed values for different metallurgical vessels.

In chapter 4, the conclusion of present investigation and suggestions for further work are enlisted.

Name of the Candidate : **UMAKANTH P.** Roll No. **9010612**

Department: **METALLURGICAL ENGINEERING**

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

During steel making the liquid steel under the protection o slag cover passes through a number of metallurgical vessels. Th typical sequence is: BOF, ladle, tundish and continuous castin mould or BOF, ladle and ingot mould. Slag carry-over betwee these vessels causes various process technological problems suc as[1,2,3]:

i. BOF slag is highly oxidizing in nature. Transfer of thi slag into ladle will impair the efficiency of various ladl metallurgical reactions such as desulphurization, deoxidation etc. during secondary processing of liqui steel.

ii. Transfer of ladle slag to continuous casting tundish wil result in accumulations of slag which may give rise t problems during sequence casting.

iii. Lastly transfer of slag to continuous casting mould may decrease the level of degree of cleanliness of the cast product and may also result in break out.

The prevention of slag carry-over during the drainage o metallurgical vessel is still an inadequately solved problem i metallurgical process technology. Vortex formation can occu already at high filling level and results in slag carry-over eve before the slag begins to flow out dur to the draining flow clos to the bottom of the vessel.

1.2 Mechanism of Vortex and Drain Sinks Formation

When a vessel is drained through the nozzle or orifice, a vortex sink will occur upon super-position of an angular momentum. When the level of bath reaches a critical height, the lighter slag phase is drawn from the surface through the centre of vortex in the form of slag strings into the nozzle. The higher the rest angular momentum in the liquid after the filling process, the sooner this phenomenon will occur[4,5].

Towards the end of draining process, the volume flow through the open channel at the ladle bottom becomes smaller than the corresponding orifice capacity. This results in a draining flow at the bottom with a hollow core in the nozzle. This phenomenon is known as drain sink, which is a major cause of slag carry-over during the draining of metallurgical vessels like ladle, tundish etc. It can be prevented by stopping the draining flow before the drain sink formation. This requires incomplete drainage of metallurgical vessels and results in loss of yield of molten steel.

1.3 Plant Observations

Plant observations show that vortex formation can take place at any stage while transfering molten metal from one vessel to another vessel.

To produce truly clean steel in the ladle, one must simply eliminate the reoxidation sources such as air reoxidation and slag/metal reaction so that rate of inclusion removal is fastar than the rate of inclusion formation. In practical terms, slag FeO + MnO levels must be reduced by slag free tapping[1].

Fig. 1.1 shows the increase in total oxygen (PPm) with increase in wt% (FeO+MnO). The slag carry-over from BOF to ladle increases the amount of (FeO+MnO)[1], so producing clean steels in the ladle becomes difficult[1].

To analyse the change in tundish slag composition during draining of ladle, chemical analysis of specimens from draining box is done. The analysis demonstrates that the change in the acidic tundish top layers is caused by highly basic desulphurization slag. Fig. 1.2 shows the change in casting rate, and lime and silica content in the tundish slag with time.

The anticipated rise in CaO and steep drop in SiO_2 coincide chronologically with abrupt drop in casting rate and confirm reliable detection of flowing slag[6].

The Fig. 1.3 clearly demonstrates that entrapment of slag by vortex at the end of casting of a ladle, is a major cause for magna-flux defects in tinplate. Steep rise in defects starts before the end of the casting of a ladle.

Both the curves are result of observations carried out at many ladle changes[3].

1.4 Origin of Vortex Formation

Vortex formation in vessels during the draining of liquid can be explained by the following way:

The effect of earth rotation has been studied[7,8] for explaining this. It has been found that the influence of earth coriolis force is negligible in normal technical flow conditions[4]. The direction of rotation is determined by the coriolis force only if the fluid has settled for a long time and

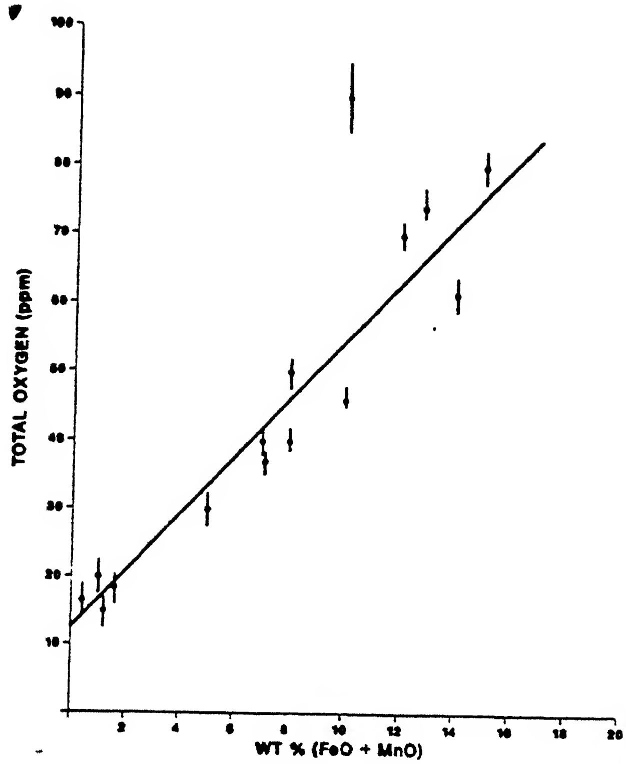


Fig.1.1 The effect of slag (FeO+MnO) content on total Oxygen content of Steel in a ladle

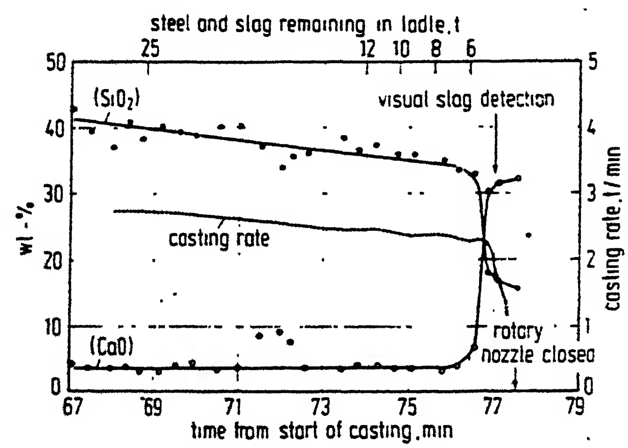


Fig.1.2 Change in tundish slag composition and casting rate during draining of ladle

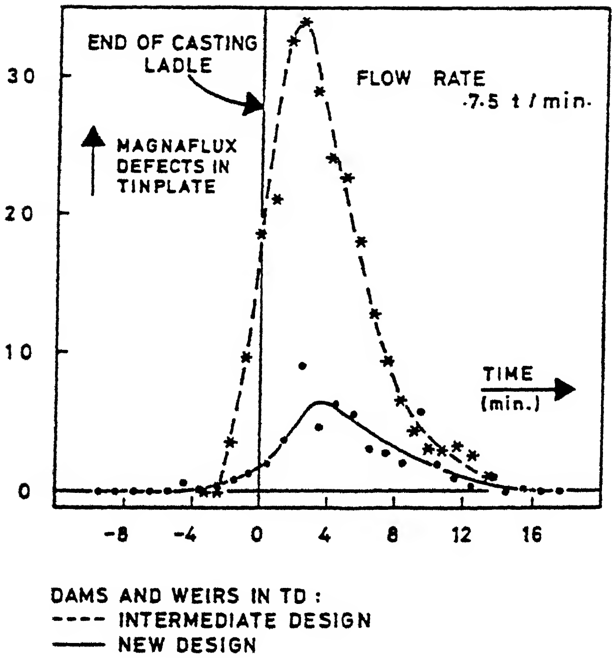


Fig.1.3 Increase in Magna flux defects at ladle change

all external disturbances are carefully avoided. Under usual practical circumstances there is always some convection with a rotational component in the vessel. When the outlet is opened the rotational flow increases due to the principle of conservation of angular momentum.

Let us assume that initially a fluid particle of mass, m, at a distance, γ_o, (eg. 300 mm) from the outlet has an angular velocity component, ω_o. Therefore, its angular momentum is equal to $m\gamma^2\omega_o$ and is conserved when the Particle reaches the orifice at radius, γ_1 (e.g. 15 mm). Hence at a radius γ_1 its angular velocity increases to $\omega_o(\gamma_o/\gamma_1)^2$. For the example considered the factor, $(\gamma_o/\gamma_1)^2$, would be 400. This simplified calculation demonstrates the enormous amplification of initial small rotation when the fluid moves to the outlet and may be the starting point for the understanding of vortex formation.

There will be three main appearances of the vortex during the drainage[4)]. They occur in sequence as dimple, surface vortex and fully developed air eutraining core which penetrates through the nozzle. The critical bath depth for the air entraining vortex is a function of outlet velocity. There are two different regimes of velocity. At small velocities (i.e. first regime), the vortex devolops at low bath depth and this bath depth increases with increasing discharge velocities until a maximum is reached (end of first regime). At a still larger discharge velocities (i.e. second regime) the critical bath depth decreases slightly with increasing discharge. The condition of interest for steel making are in second regime. Hence the conclusion of Hammer Schimid[4)]

may also be valid, in principle for the draining of liquid steel, namely:

(1) The critical bath depth for air eutraining vortex increases with increasing initial circulation in the vessel.

(2) The diameters of the vessel has little influence on vortex formation.

(3) The vortex develops at a lower bath depth as the outlet diameter is increased. Hammer Schimid[4] et al. have studied vortex formation during drainage of metallurgical vessels. The results show that vortex formation can be suppressed effectively by obstacles near the nozzle. Modified outlets, and fixed or floating discs and balls do not have much influence. Once a vortex has been formed, temporary closing of the outlet does not eliminate vortex. After renewed opening the vortex reappears after a short time.

An eccentric instead of central position of nozzle is very effective in delaying the vortex formation. Rolf' Steffen[6] et al. have studied Fluid flow Phenomena of Metal and Slag during drainage of metallurgical vessels. The results show that flow breaker which prevent the development of vortex sinks, would be virtually ineffective as counter measure against drain sinks. Tilting of the ladle with the nozzle arranged close to the ladle wall and the slanted lining or stepping of the ladle bottom, will be effective in case of drain sinks. They have also explained the effect of eccentricity that increasing the eccentricity decreases the critical bath depth at which vortex will form.

Hans-Jurgen[5] et.al. studied the slag carry over in sequence casting of steels. In this work they have studied the measurement of slag-carry over.

Paul [10] et al., Larry Daggett[11], Marwin Sibulking [12] and Enzo Levi[13] have studied vortexes in Hydraulics.

The results [10,11,12,13] show that vortex formation is not influenced by Surface Tension and Viscosity of the liquids.

1.5 Present Work

The aim of the present work is to elucidate the conditions for vortex formation and to study the effect of variables i.e nozzle diameter, eccentricity, waiting time, filling rate and mode of filling.

For this purpose model experiments with water and oil as the modeling fluids have been conducted in the laboratory. The present investigation has been confined to the draining flow where the liquid level decreases with time.

In the experiments water is drained through a nozzle without oil cover or with oil cover. The discharge of water is continuously recorded and vortex height and time are studied.

CHAPTER TWO

EXPERIMENTAL

2.1 Model Vessel

The perspex vessel is in square cross section with 570mm side, height of the vessel is 440mm. The volume of the vessel is 0.143 m^3. Provisions are made to insert nozzles of different diameters at different locations i.e. concentric and eccentric positions. Brass adopters are made for each nozzle to couple it with the vessel. Fig. 2.1 shows the details.

a) The nozzles used are straight bore type. Length of the nozzle is 40 to 80mm and diameter varies from 16 mm to 39 mm. The nozzles are fabricated either of perspex glass or mild steel. The nozzle is fitted in such a way that the upper surface of it matches with the bottom of the vessel.

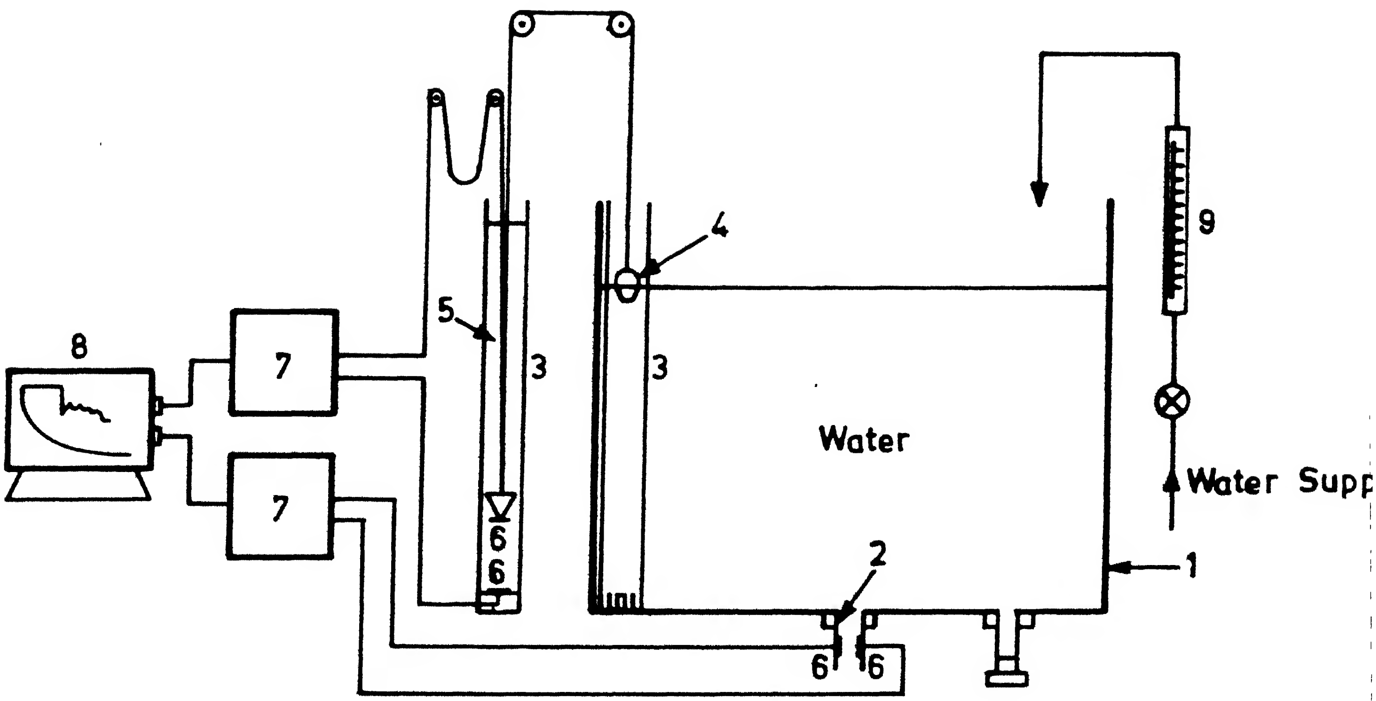
A flowmeter is connected to the main water supply. Inlet water flow rate is controlled with the help of a slide gate valve. The detail features of the experimental set-up have been shown in Fig. 2.1.

2.2 Water Level Measurement

Principle - The electrical conductivity measured between two electrodes in a liquid column is inversely proportional to the distance between the eloctrodes.

In order to measure the waterlevel, a 40 mm cylindrical tube with rectangular slots at the bottom, is fixed at one corner of the vessel.

The rectangular slots are made to keep the water level in the vessel and cylindrical tube at same level.



1. Perspex Vessel 2. Perspex Nozzle 3. Cylindrical Tube 4. Float 5. KCl Solution 6. Platinum Probe 7. Conductivity Meter 8. Dual Pen Recorder 9. Flow Meter.

Fig.2.1 Experimental set up

A float is introduced into the cylindrical tube with a cord. The other end of the cord is connected over the pulleys to a platinum probe in another cylindrical tube which is kept outside the vessel. A small weight in conical shape is attached to the probe as shown in Fig. 2.1 in order to straighten the movement of probe in the cylindrical tube. Conical shape offers least resistance to motion due to the movement of probe in cylindrical tube.

To counter balance the weight of probe, another weight in the shape of conical teflon piece is fixed to the bottom of the float. Due to this counter weight, 2 cm of the float will remain below the water surface as shown in the Fig. 2.1. This cylindrical tube contains potassium chloride (KCl) solution. The solution is prepared by dissolving 0.75 gms of KCl in 1000 ml of distilled water (solution of any strength could be taken). At the bottom of this tube another Platinum Probe is fixed.

The electrical circuit which is made to measure the water level, consists of a conductivity meter and two Platinum Probes which are placed in the cylindrical tube containing KCl solution.

The float in the cylindrical tube within the vessel moves with the water level, so that Platinum Probe connected to it also moves in the KCl solution tube. Because of the movement of the probe, the distance between the two probes varies in the KCl solution tube. Because of this the conductivity measured between the probes by the conductivity meter changes according to the water level variation in the vessel. The signal comming in m.v. through the conductivity meter is given to the duel pen recorder.

The conductivity meter has sp. conductance range from 30μmho to 20μmho, and cell constant range from 0.9 to 1.1.

The dual pen recorder used has the chart speed range from 2.5 cm per minute to 25 cm per minute. The range of full scale m.v. is from 10 m.v. to 10 V.

2.3 Vortex Detection

The principle of the vortex measurement, is that when air mixes with water it changes the electrical conductivity of water. This change in electrical conductivity can be measured by using an electrical circuit.

To measure the conductivity of the draining water, two Platinum Probes are fixed in the nozzle as shown in the Fig. 2.1. The Platinum Probes used are square in cross-section with 4 mm side and negligible thickness. The electrical circuit which is made to detect the vortex formation consists of a conductivity meter and two probes which are fixed in nozzle. The conductivity meter measure the resistance between the probes and gives the output signal in m.v.

In the normal condition when only water is flowing through the nozzle, the strength of signal is uniform. But when air enters the nozzle during the vortex formation, a sudden drop occurs in the signal strength. The m.v. signal as obtained through conductivity meter are recorded on a duel pen recorder to measure the sudden drop in conductivity indicating the vortex formation.

2.4 Calibration of Water Height vs. Millivolts

The variation of water level in the perspex vessel has been measured in terms of millivolts as recorded by conductivity meter. A standard calibration method is adopted for calibration of height by using a digital multimeter.

In brief, the method consists of filling the vessel with water to different levels and corresponding to these levels of water, the probe which is in the cylindrical tube containing KCl solution, will move due to the movement of float in the cylindrical tube with in the vessel. Corresponding to the each level of water column the m.v. signal obtained through conductivity meter is measured by a digital multimeter. Under the present experimental conditions, calibration of water height vs. m.v. could be done between 40 cm and 2 cm in the vessel. When the water level reaches 1.8 cm, the bottom of the float touches the bottom of the vessel which results in no movement condition of the Pt probe as a consequence of which no change in the m.v. output signal. With the noted values of height of water level and corresponding millivolts, a regression function is obtained. The regression function is as follows.

$$V = 4.34 - 0.0012H + 0.004H^2 \qquad (2.3)$$

In the above equation V is in m.v. and H is the height of water level expressed in cm. This equation is valid between 40 cm and 2 cm because of the above mentioned reasons. The calibration graph shown in Fig. 2.2 shows the experimental data points and a correlation line as obtained from eq. 2.3. The graph shows that the eq. 2.3 reproduces water level heights and milivolts values.

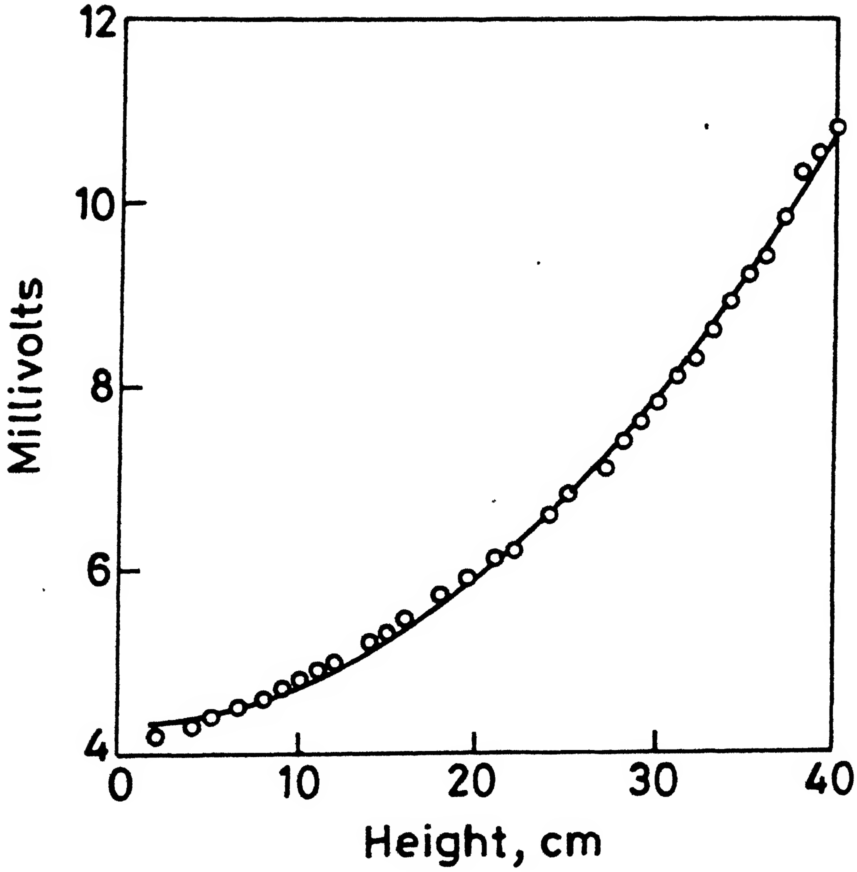


Fig.2.2 Calibration Curve

2.5 Experimental Procedure

The sequential procedure followed for the present work has been briefly described below. Before starting the experiment, the following adjustments are made.

(a) The power supply to the conductivity meters and duel pen recorders is put on.

(b) The chart speed of duel pen recorder is adjusted so as to make the signal more distinguishable. The speed is varied from 2.5 cm/min to 5 cm/min and is adjusted according to the discharge rate of water from nozzle.

(c) The specific conductances of both the conductivity meters are adjusted so as to read the signals more clearly. 20 mMho is set for the conductivity meter which detects vortex formation.

(d) The full scale m.v. range of duel pen recorder is adjusted to 10 m.v. to match with the signals coming from the conductivity meters.

After the priliminary adjustments have been done, water inlet valve is opened and the inlet flow rate of water is adjusted to a desired value with the help of a flow meter. When the water level reaches to the required height, the inlet valve is closed. After a particular waiting time, the outlet is opened.

As the water level in the vessel decreases, the probe connected to the float moves correspondingly. The output signals obtained through the two conductivity meters are continuously recorded on a duel pen recorder.

2.6 Experimental Variables

The following experimental variables are studied in the present work.

(a) **Inlet flow rate** - Inlet low rates ranging from 175 m lit/sec. to 377 m lit/sec. are studied in the present work.

(b) **Nozzle diameters** - Nozzles of straight bore type having diameters of 16 mm, 25 mm, 30 mm, 37 mm and 39 mm are chosen for the present work.

(c) **Waiting time** - It is the interim time after filling the vessel to the required level and before the opening of the nozzle.

Waiting time ranging from 30 sec. to 1500 sec. is studied in the present work.

(d) **Eccentricity** - Eccentricity is the measure of the deviation from the centre. The nozzle is fixed either at the centre of the vessel or at the 0.5 eccentricity.

(e) **Mode of filling** - The mode of filling is the way in which the vessel has been filled. In the present work the following modes are studied.

(a) Axial filling ($\theta=90^\circ$)

(b) Tangential filling ($\theta=0^\circ$)

(c) Intermediate modes of filling ($\theta=30^\circ$, 60°)

CHAPTER THREE

RESULTS AND DISCUSSIONS

In this chapter both photographic observations and quantitative results are presented and discussed.

3.1 Photographic Observations

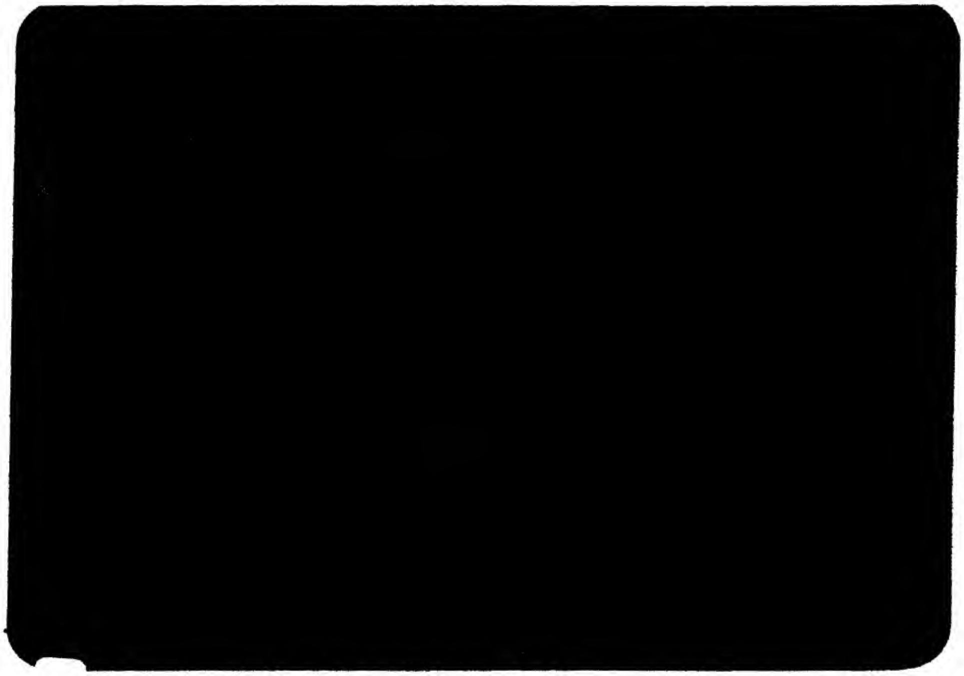
Photographs are taken after opening the nozzle in order to record the various stages of vortex formation for different experimental conditions. For this purpose coloured cyclohexane is added at the top of the water bath.

3.1.1 Vortex Formation

The flow rate of the inlet water is kept at 250 ml/sec and the vessel is filled with tangential mode of filling. After 60 seconds of waiting time, the nozzle is opened. Fig. 3.1 shows the 3 different stages of vortex formation.

For a critical water depth of 200 mm, photographs 3.1a and b show the dimple formation after 32 and 32.5 seconds after opening the nozzle, respectively. The entraining vortex (photograph 3.1c) and a fully formed vortex (photograph 3.1d) are observed after 33 and 34 seconds, respectively.

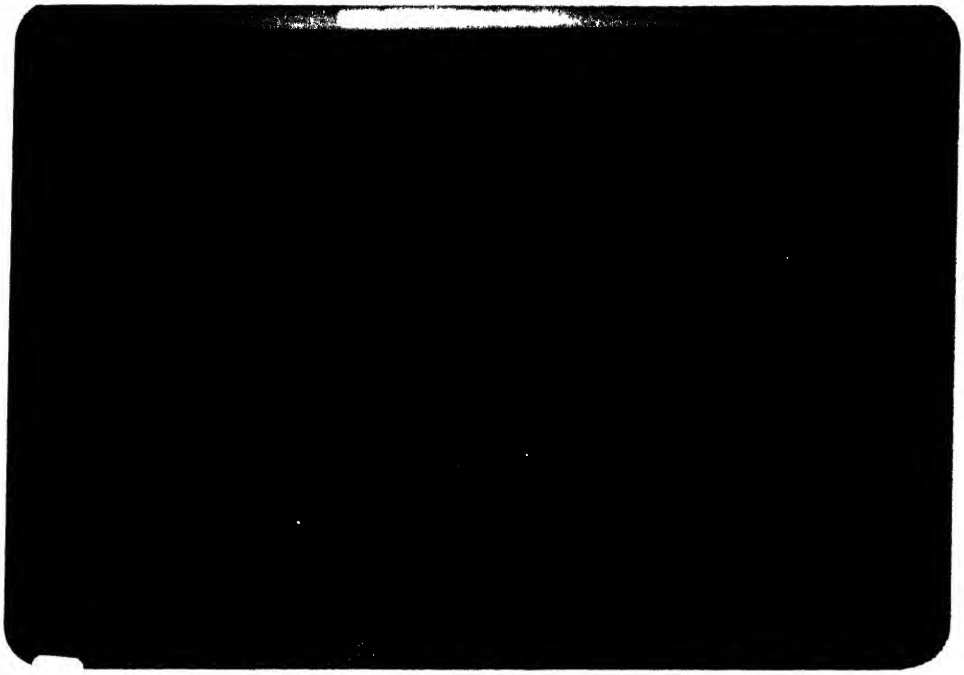
Rotational velocity increases while discharging and when it reaches to a critical value, a low pressure is created due to centrifugal force leading to dimple formation. Further increase of rotational velocity causes the air core entrainment into the bath. The vortex entrains into the nozzle. It is called entraining vortex (photograph 3.1e). It is clear from the photographs taken while discharging, vortex formation occurs in 3 stages: dimple, entraining vortex and full developed vortex. A



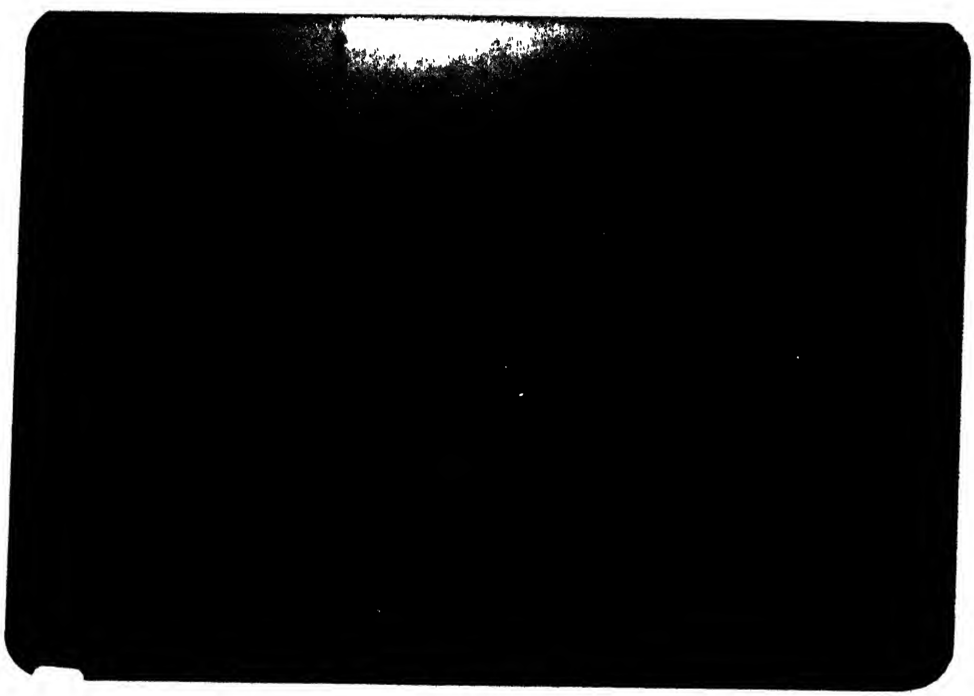
a) Time = 32 sec.

b) Time = 32.5 sec

Fig.3.1 Photographs showing different stages of Vortex formation



c) Time = 33 sec



d) Time = 34 sec

time interval of the order of 1.5 seconds is noted between dimple formation and fully developed vortex formation.

3.1.2 Stream Flaring

Photographs of the stream are taken for the experimental conditions mentioned in Section 3.1.1. Photograph 3.2a shows the cylinder like stream when there is no vortex formation. Photograph 3.2b and c are taken at the time of vortex formation and show the flaring of stream.

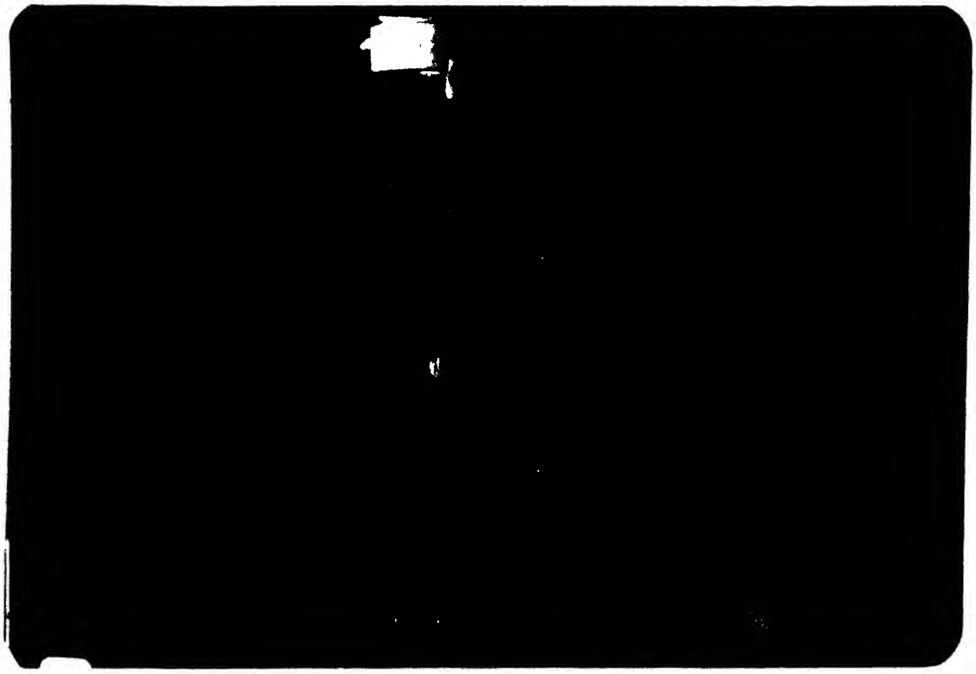
Flaring of the stream is caused by the expansion of the entrained air core when it leaves the nozzle. Photograph 3.3 shows the carry-over of cyclohexane with the stream because of the vortex formation.

3.2 Quantitative Results

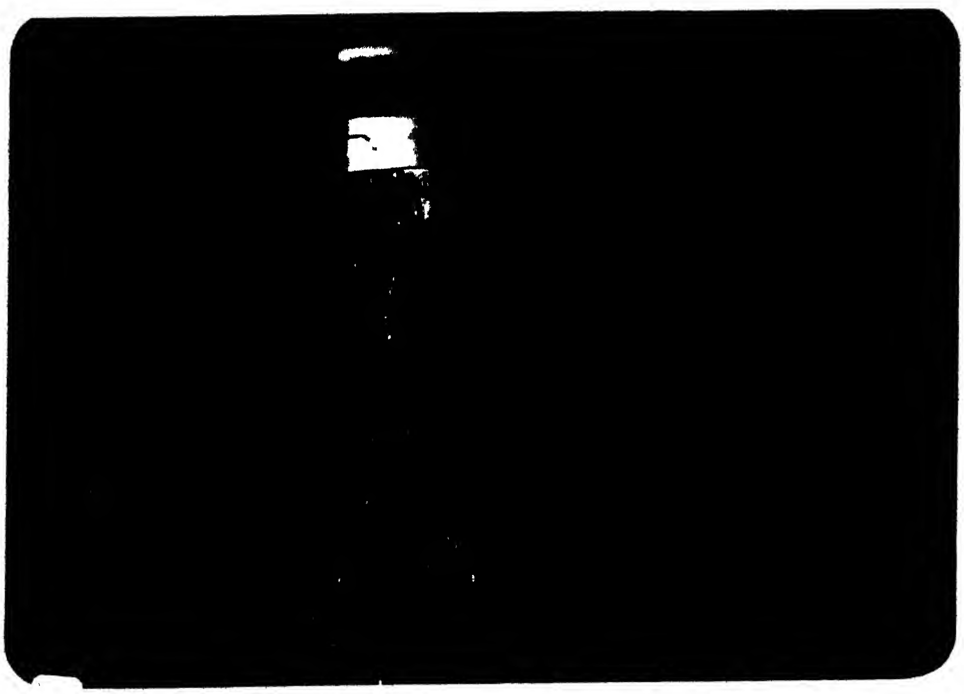
Around 600 experiments with different variables are conducted to study the vortex formation. In all the experiments the decrease in water bath level is recorded as a function of time and vortex formation is detected by superimposing two signals. Figs. 3.4 and 3.5 show the typical recordeds outputs obtained in the experiments. The inserted Picture in the figures show the experimental conditions for that particular experiment.

In the recorded graphs, two curves can be observed. The smooth curve represents the variation of water level with time in terms of m.v.

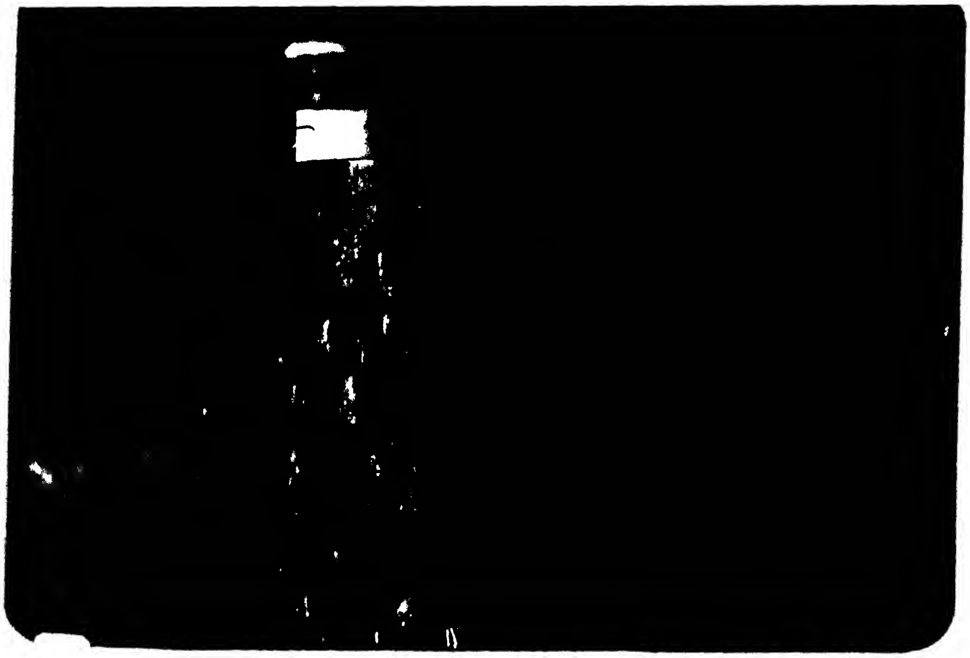
The maximum value of the signal in both the figures is 10.8 m.v. when the water level is 40 cm. The minimum value of the signal is 4.2 m.v. for the present experimental conditions when the water level is 1.8 cm in the bath.



(a) Time = 40 Sec



(b) Time = 70 Sec



(c) Time = 75 Sec

Fig.3.2 Photographs showing the Flaring of the Stream

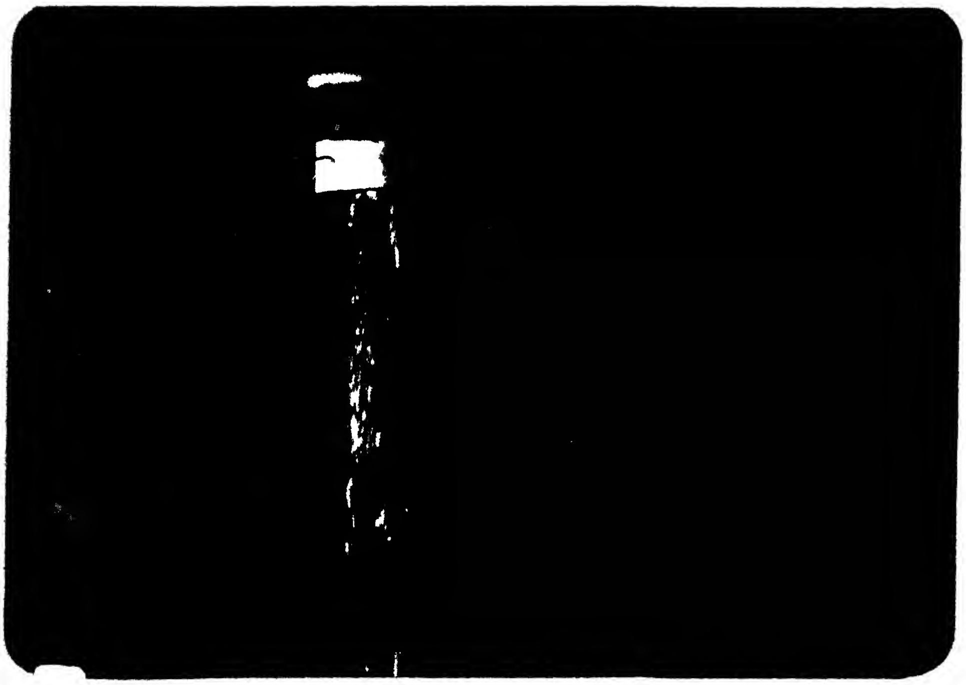


Fig.3.3 Photograph showing the entrainment of the Cyclohexane

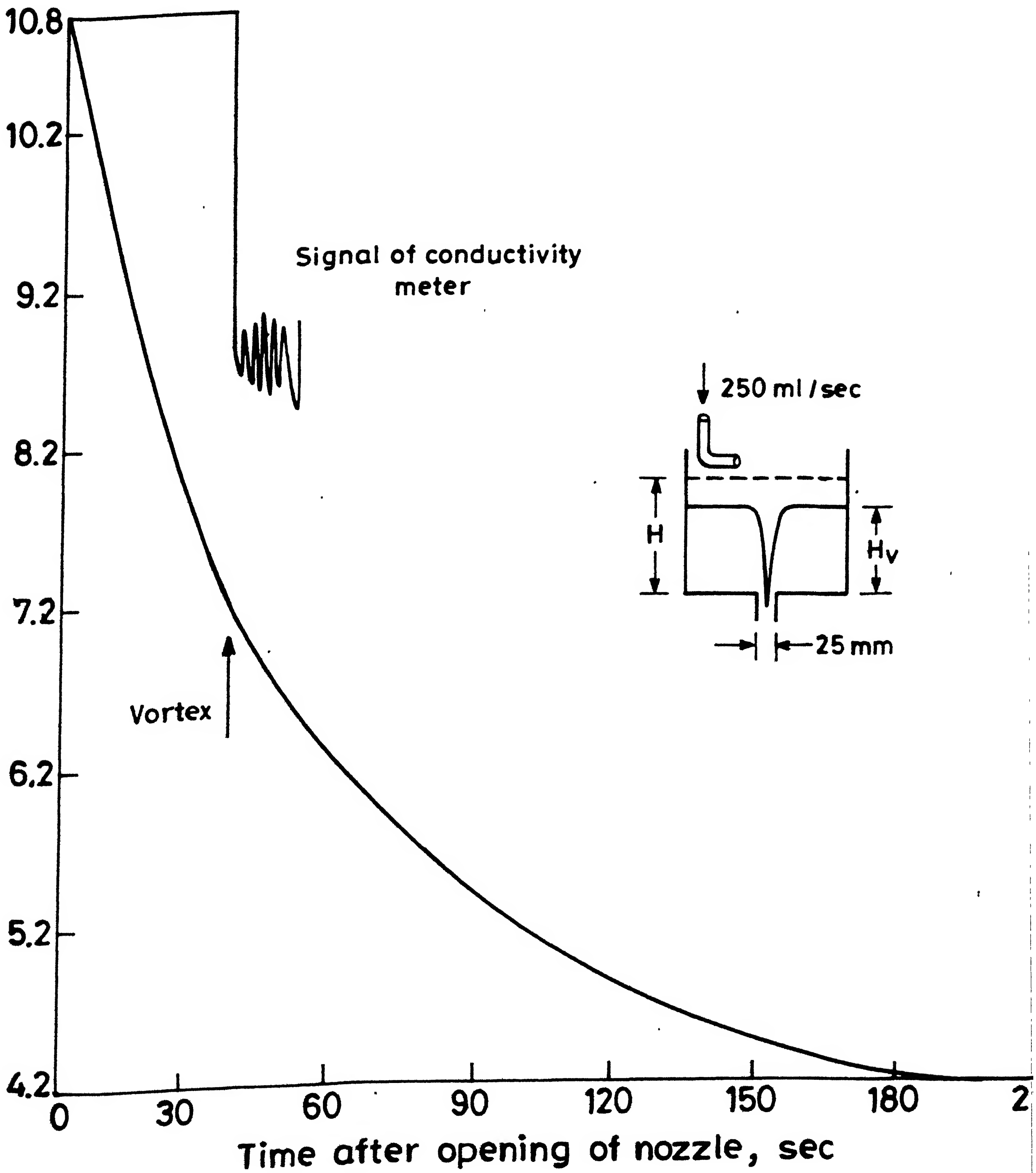


Fig.3.4 Typical recorded output obtained from duel pen recorder for tangential mode of filling

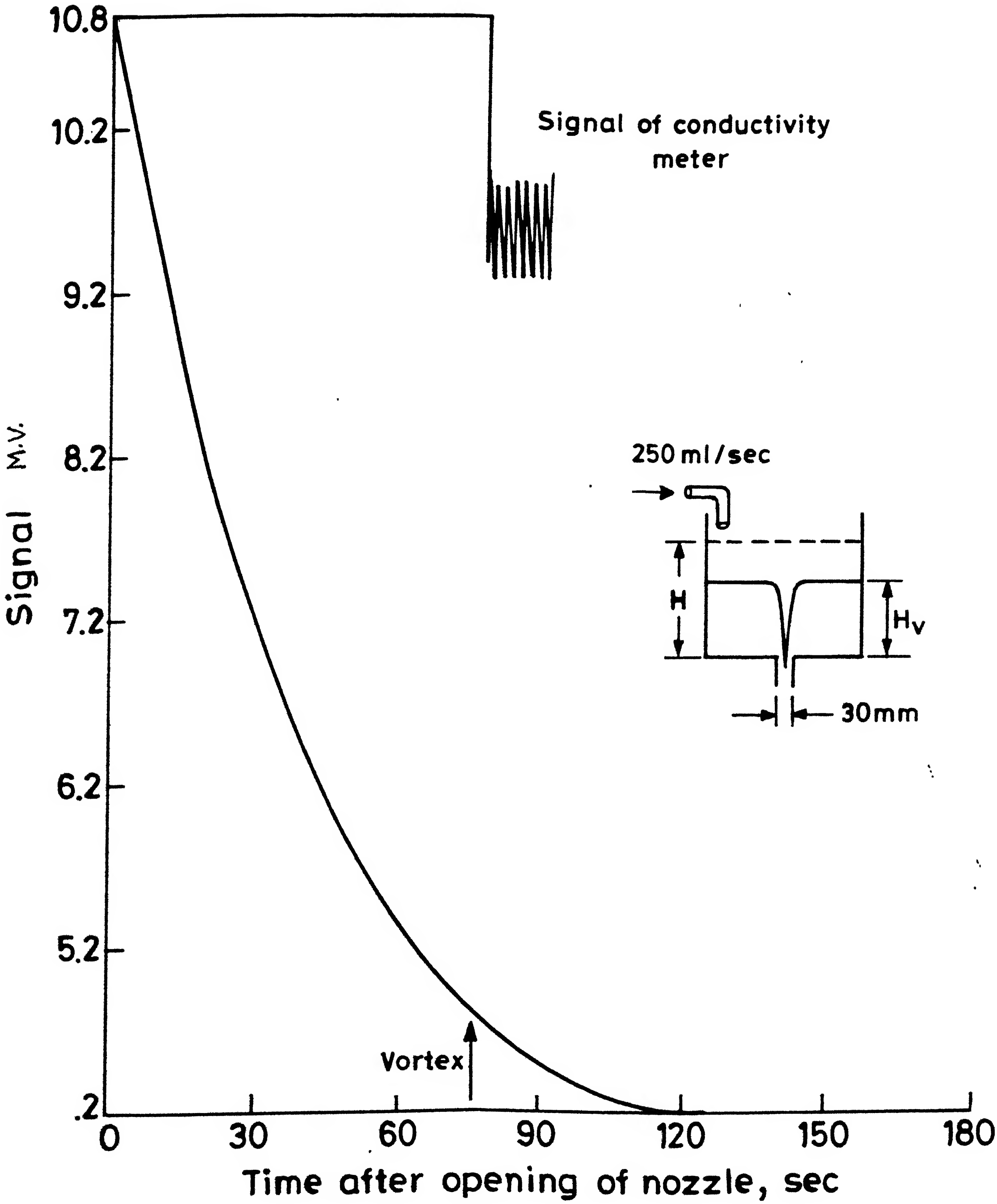


Fig.3.5 Typical recorded output obtained from duel pen recorder for axial mode of filling

The another curve in the figures shows the variation of m.v. measured in the nozzle with time. The strength of the signal is 10.8 m.v. it can be seen that the strength of the signal does not change upto the critical value of time.

Beyond the critical time, there is sudden drop in the strength of the signal i.e. when the vortex formation occurs.

More than 150 experiments are rep eated for checking the reproducibility under wide varying experimental conditions. Reproducibility is checked by observing the vortex time and vortex height. In almost all the experiments same values of vortex height and time are obtained under identical condition of the experiments.

The value of the m.v. are read from the recorder output curves and these m.v. values are converted into water level height with the help of calibration curve. Figs. 3.6 to 3.14 show the typical discharge graphs. Inserted picture in the figures show the experimental conditions for that particular experiment. The figures 3.6 to 3.14 show the decrease in water level with time as a function of waiting time. Waiting time is varied in the range of 30 to 1500 seconds depending on the other experimental conditions. The arrow marks in the figures show vortex time and vortex height for the given conditions.

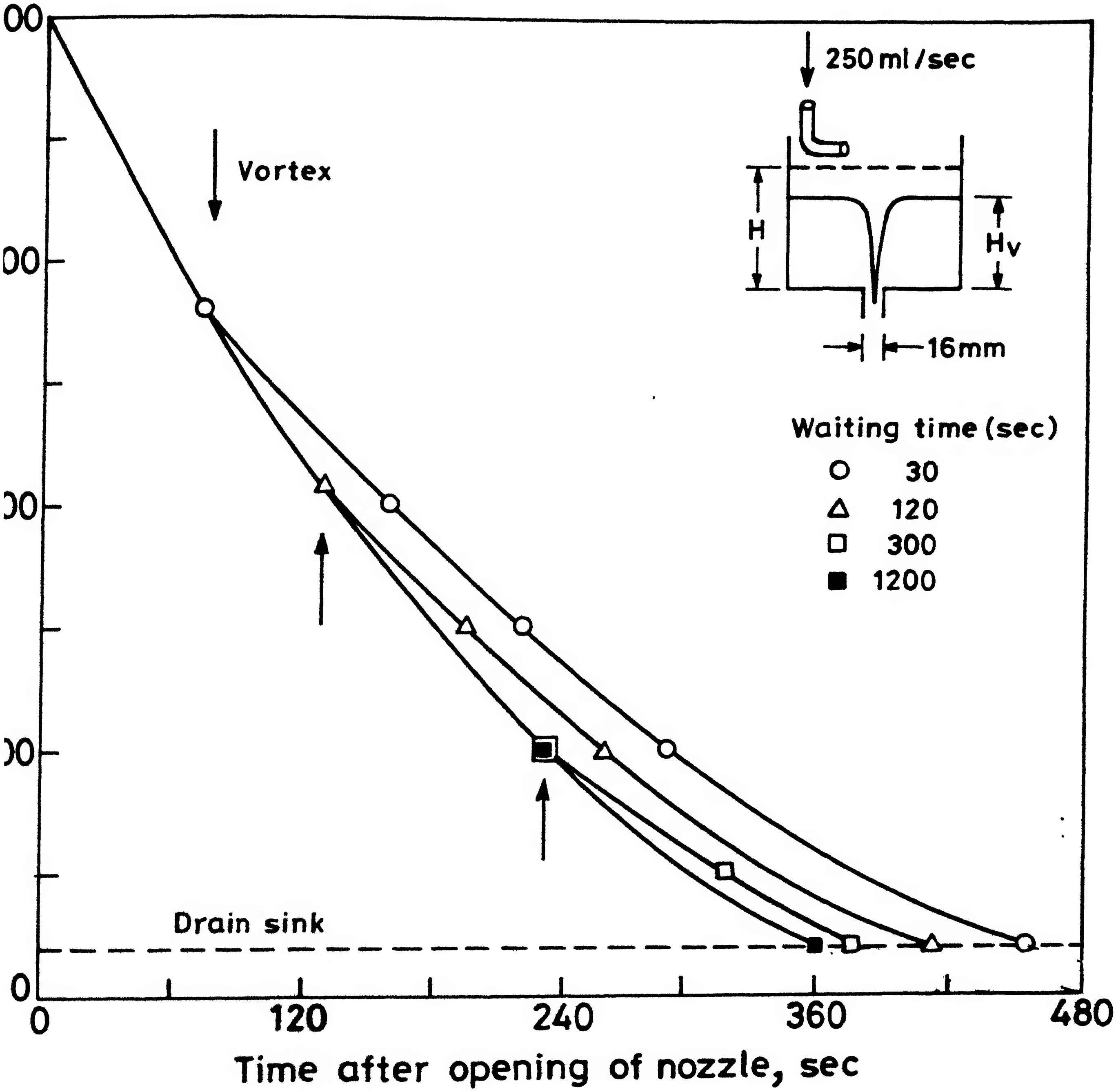


Fig.3.6 Discharge curve showing the variation of water height with time after opening of nozzle for different waiting times

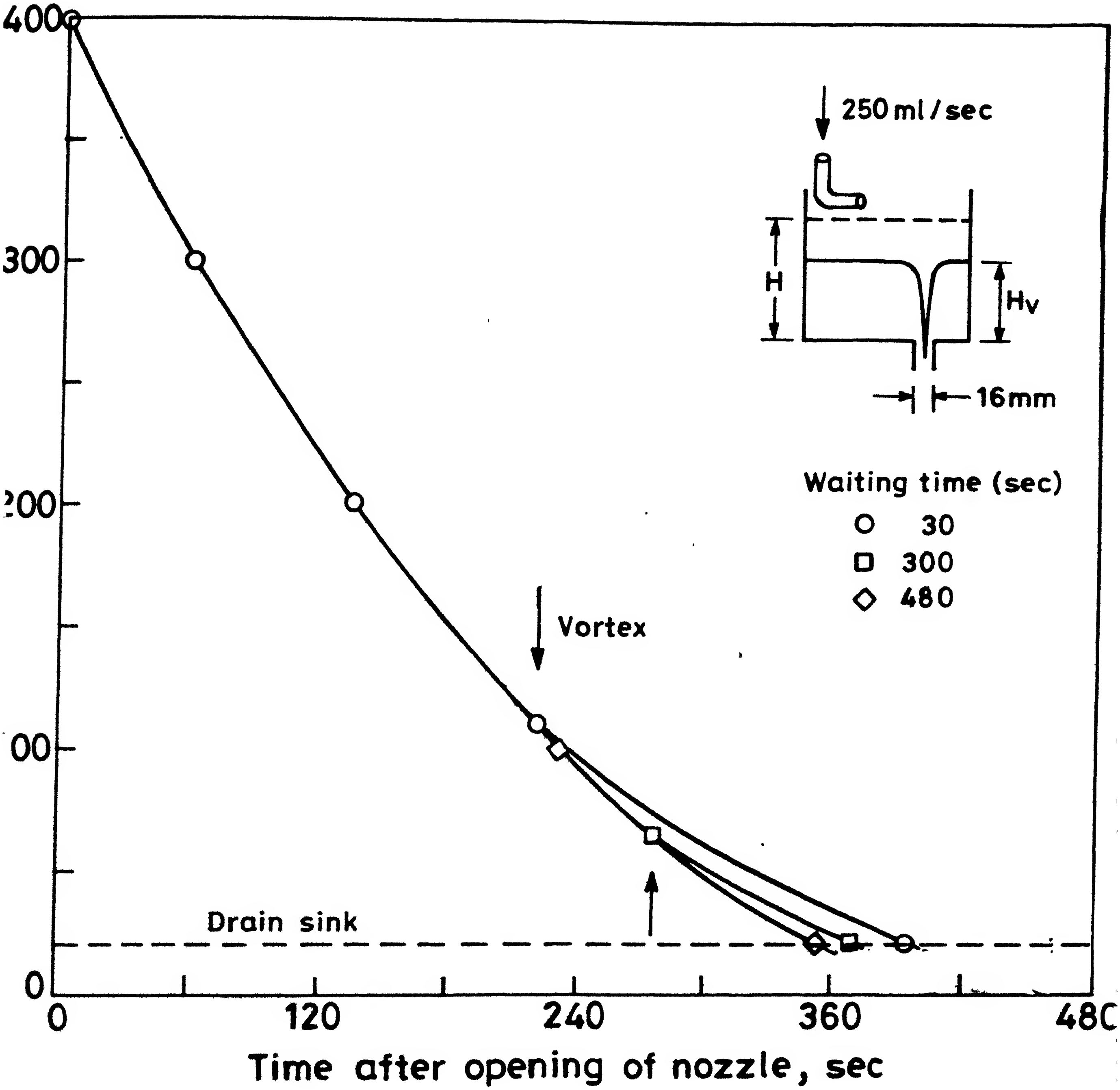


Fig.3.7 Discharge curve showing the variation of water height with time after opening of nozzle for different waiting times

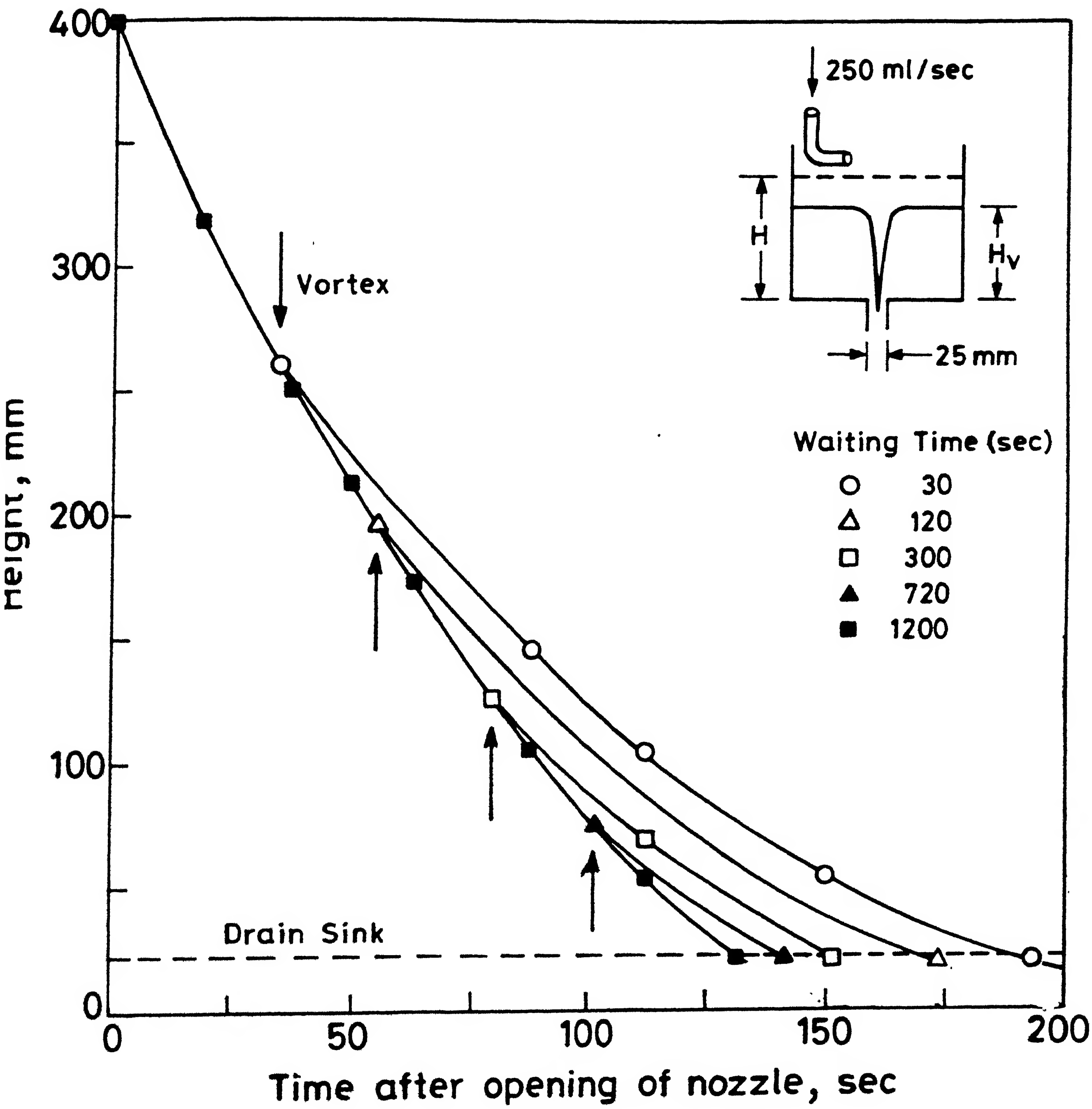


Fig.3.8 Discharge curve showing the variation of water height with time after opening of nozzle for different waiting times

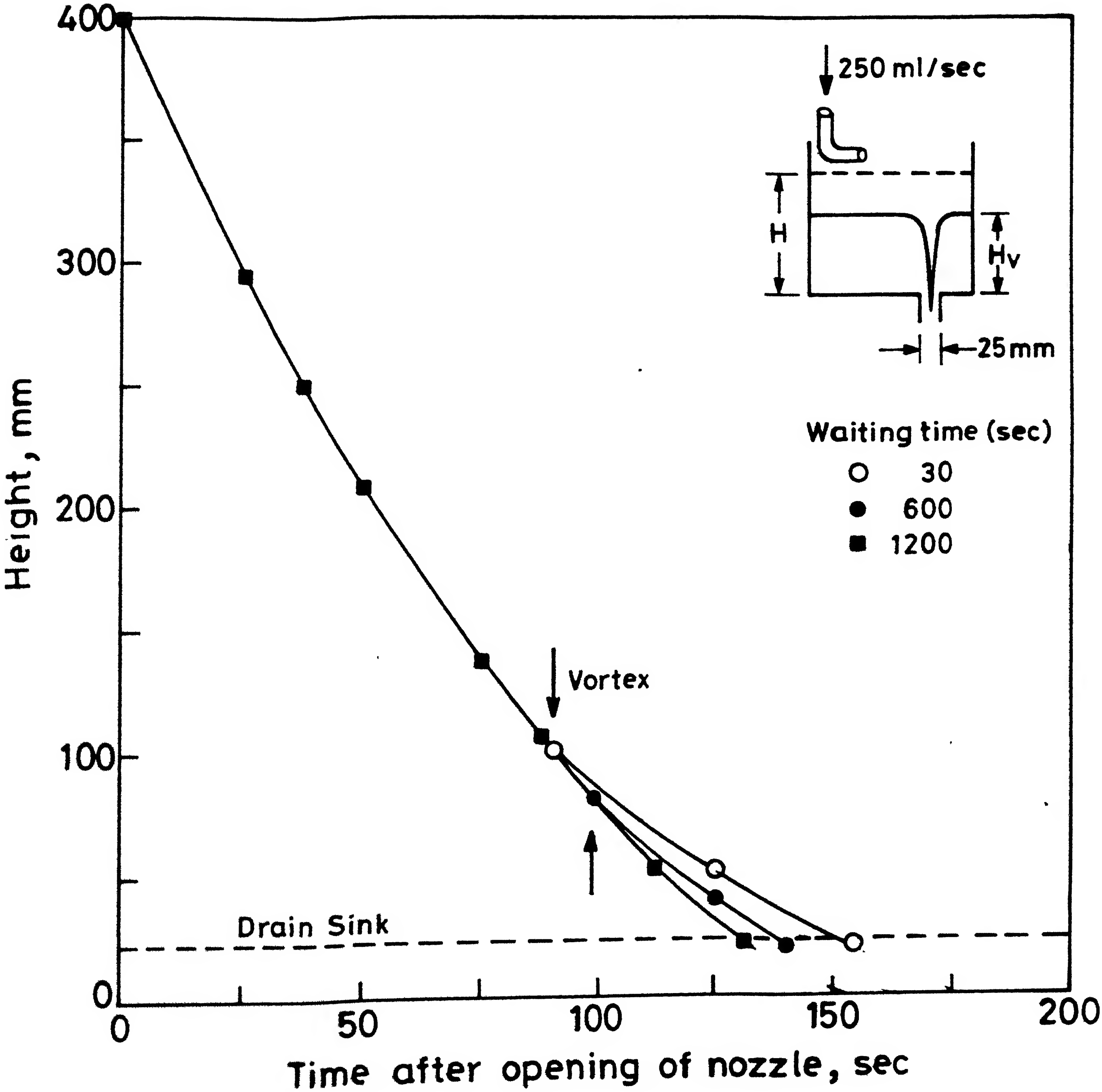


Fig.3.9 Discharge curve showing the variation of water height with time after opening of nozzle for different waiting times

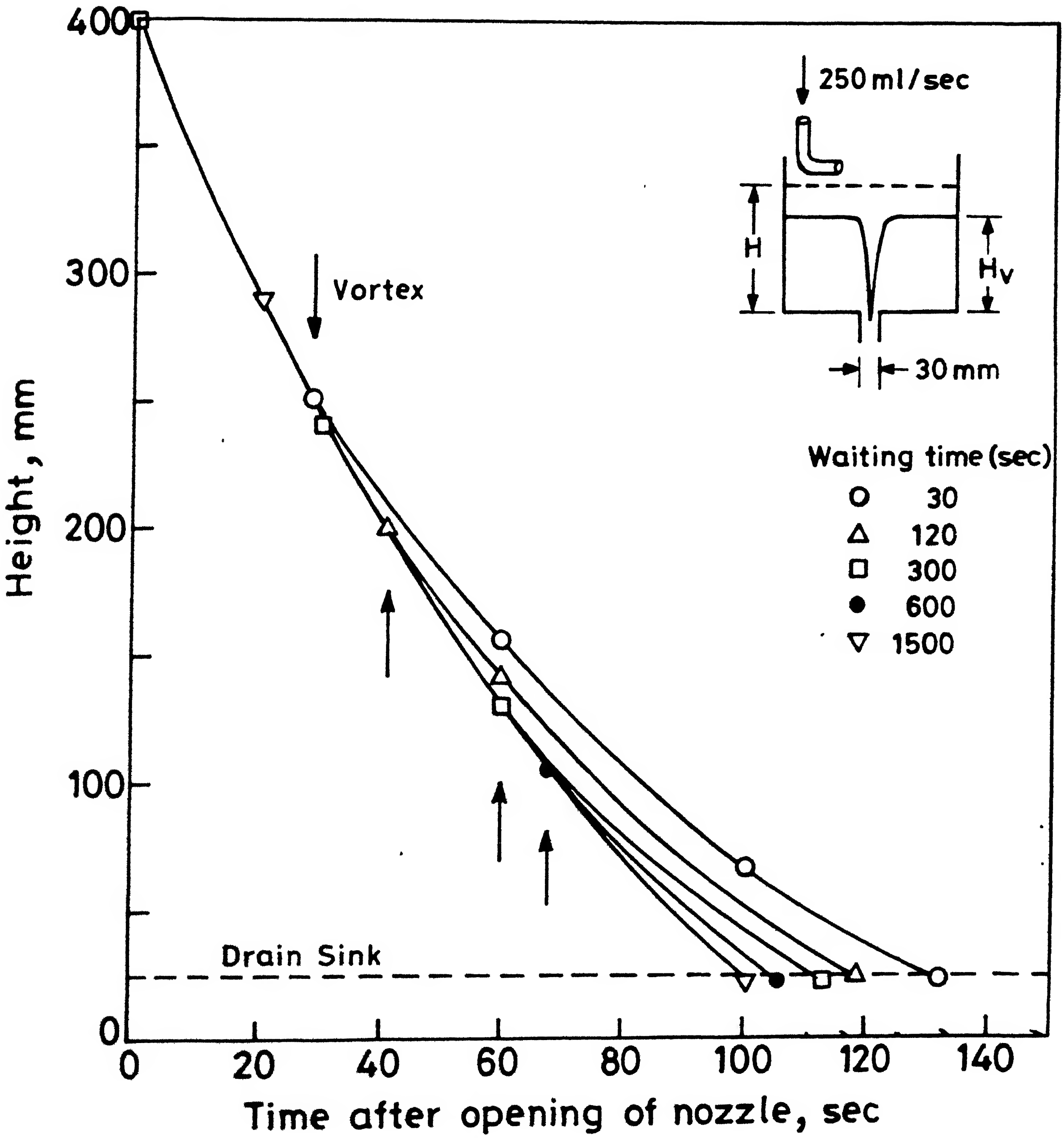


Fig.3.10 Discharge curve showing the variation of water height with time after opening of nozzle for different waiting times

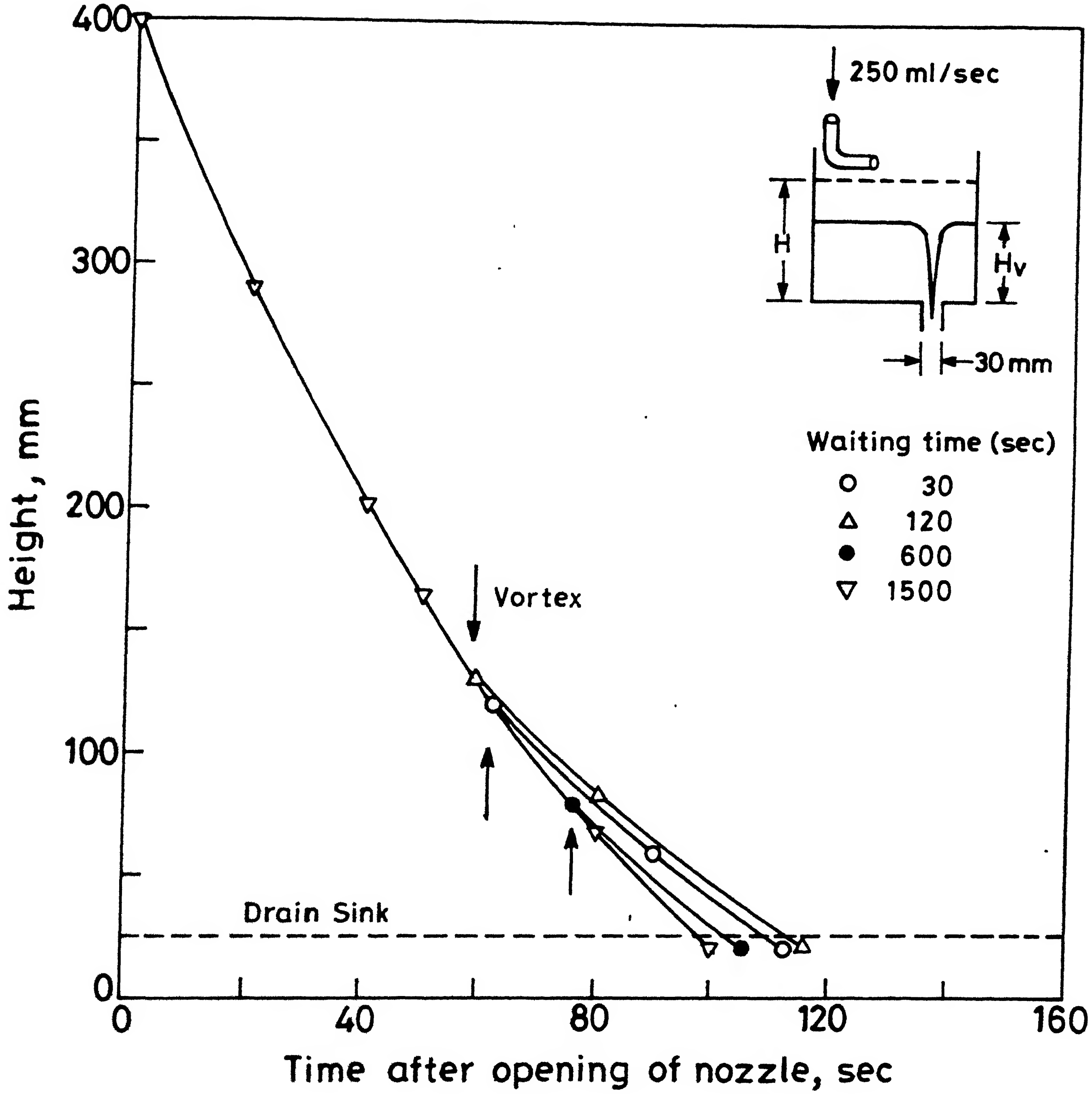


Fig.3.11 Discharge curve showing the variation of water height with time after opening of nozzle for different waiting times

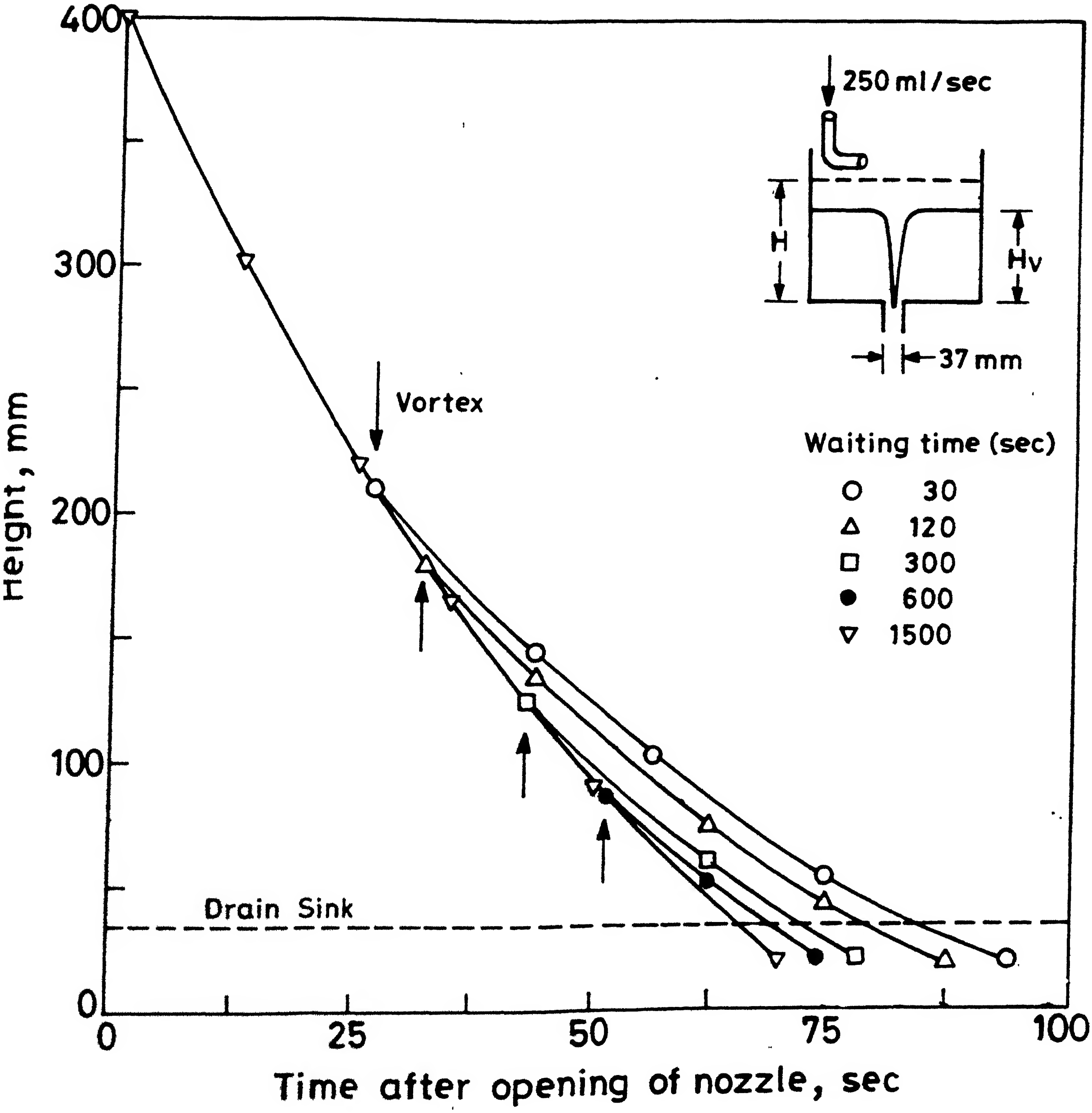


Fig.3.12 Discharge curve showing the variation of water height with time after opening of nozzle for different waiting times

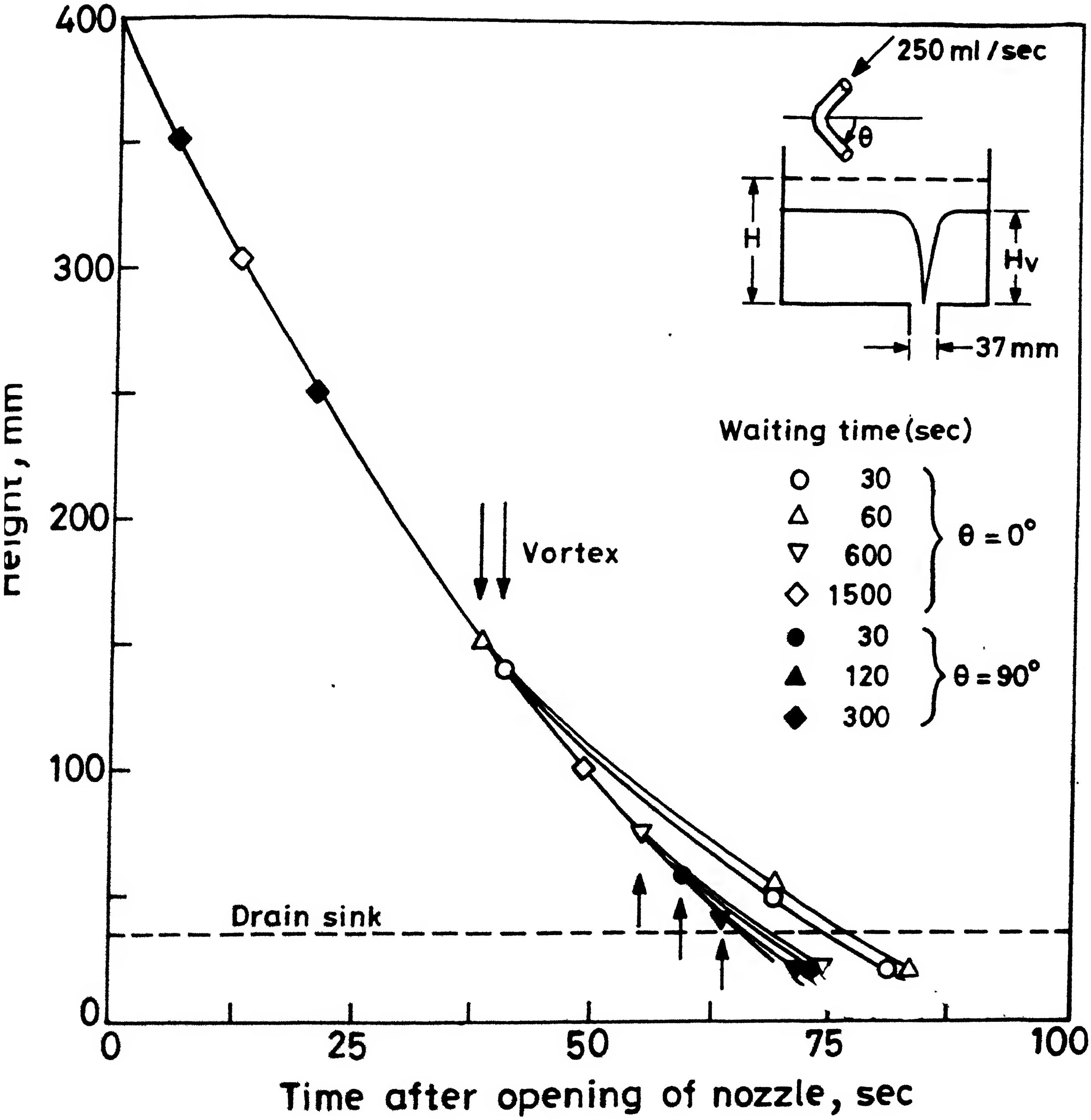


Fig.3.13 Discharge curve showing the variation of water height with time after opening of nozzle for different waiting times

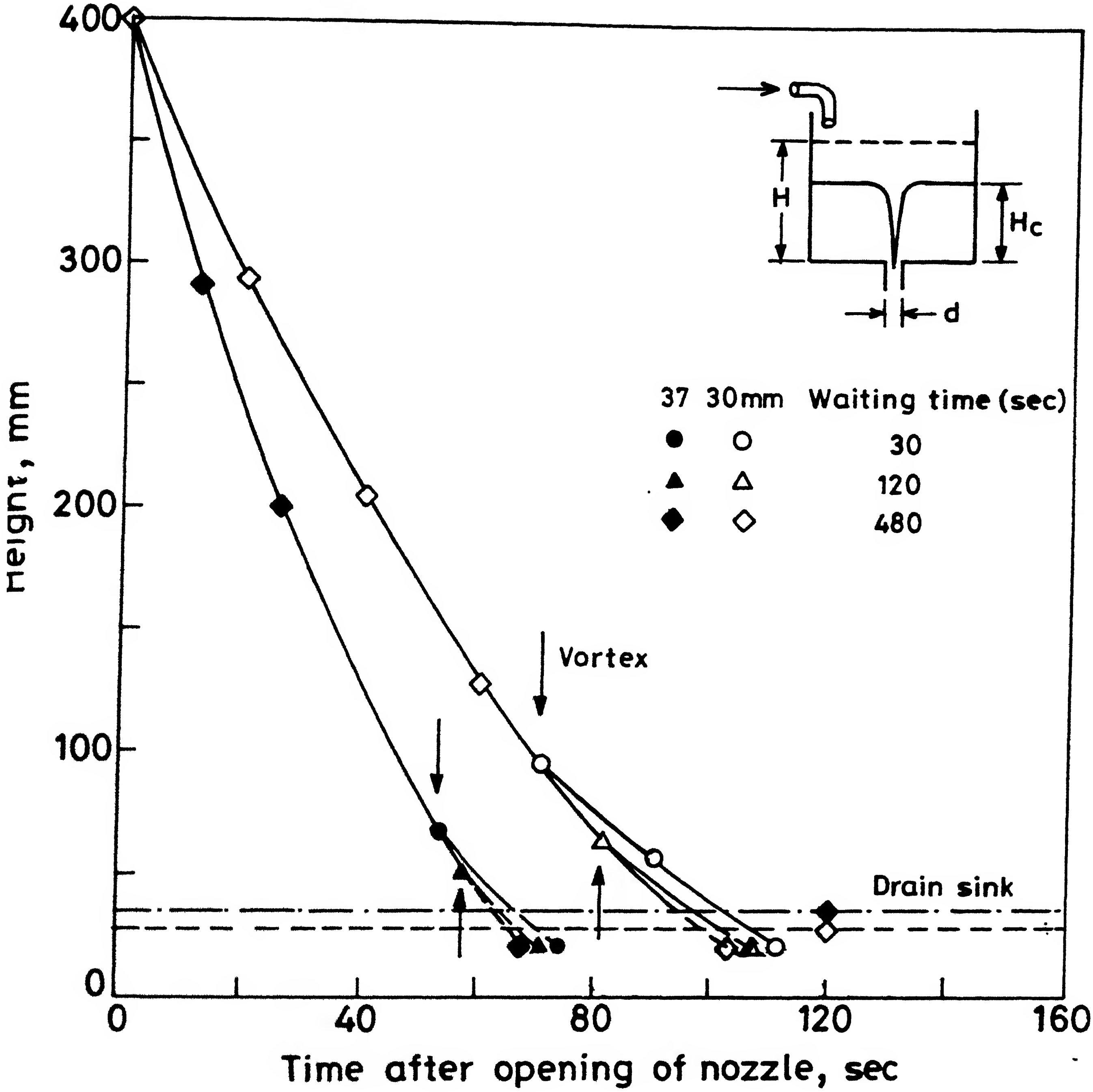


Fig.3.14 Discharge curve showing the variation of water height with time after opening of nozzle for different waiting times

These figures clearly show that vortex height and time are effected by flow rate, waiting time, diameter of nozzle, eccentricity of nozzle and mode of filling.

Total time for draining is found to depend upon waiting time. For 30mm nozzle diameter the total draining time was 200 sec for 30 sec waiting time. The draining time ws found to decrease with increase in waiting time at 60 sec waiting time draining time was 170 sec and at 1500 sec waiting time it was 135 sec.

Vortex height and time and time to discharge of the given amount water are noted from the figures. All the vortex height, time values are given in Tables 3.2 to 3.7.

3.2.1 Vortex height

Vortex height is studied as a function of waiting time, flow rate, eccentricity, diameter of nozzle and mode of filling.

3.2.1.1 Effect of Waiting Time

Waiting time effect on vortex height is studied for different modes of filling for centric and eccentric nozzles.

Fig. 3.15, 3.16 show the variation of vortex height as a function of waiting time for different flow rates and for centric and eccentric nozzles. Nozzle diameter is 25 cm. On the abscissa, the waiting time between the end of filling and the opening of nozzle is given. Hence this scale is a measure of the intensity of rotation in the water existing at the moment the nozzle is opened. It can be observed from the figure that increasing waiting time decreases the vortex height. When the vessel is filled, rotational component in the bath is developed. When the water is discharged, the angular velocity increases

considerably when a particle away from the centre reaches to the centre because of the conservation of momentum. In this process if the velocity reaches the critical velocity, vortex will form. The higher is the rotational component in the bath, the sooner the critical velocity reached, which leads to vortex formation.

The 'Waiting time' given before the opening of nozzle reduces the initial rotational component which is created due to the filling of the vessel. If the rotational component in the vessel is low, time to reach the critical velocity is delayed. In that time the outlet nozzle discharges more amount of water, before the vortex formation takes place. So increase in waiting time decreases the vortex height.

For centric nozzles it can be observed from the Fig. 3.15 that increasing the flow rate increases the vortex height. It is also clear that for waiting times less than 300 sec, increases in vortex height is more prominent than for the waiting times above 300 sec. For 120 sec waiting time, the variation in the vortex height between maximum and minimum flow rate is 55 mm, whereas for waiting time of 480 sec. and 600 sec., the variation in vortex height is 28 mm and 25 mm, respectively.

Initial rotational component in the vessel is produced due to the inlet flow. Increase in inlet flowrate increases the rotational components developed due to the filling of the vessel. Because of the increase in initial rotational flow, critical rotational velocity is reached early, while discharging. The earlier is the critical rotational velocity reached sooner the vortex forms. So vortex height increases with increase in inlet

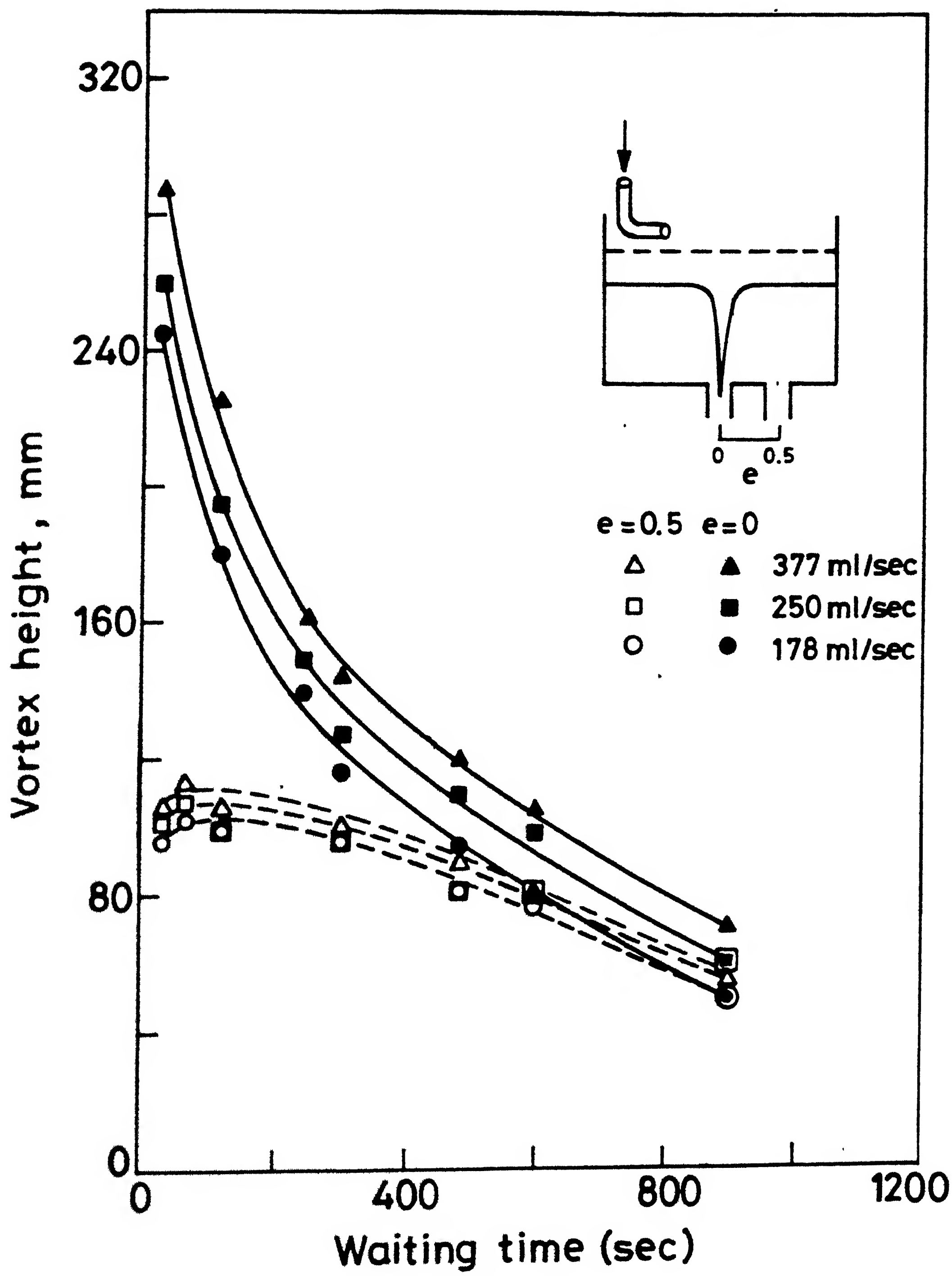


Fig.3.15 Effect of waiting time on Vortex height for different flow rates

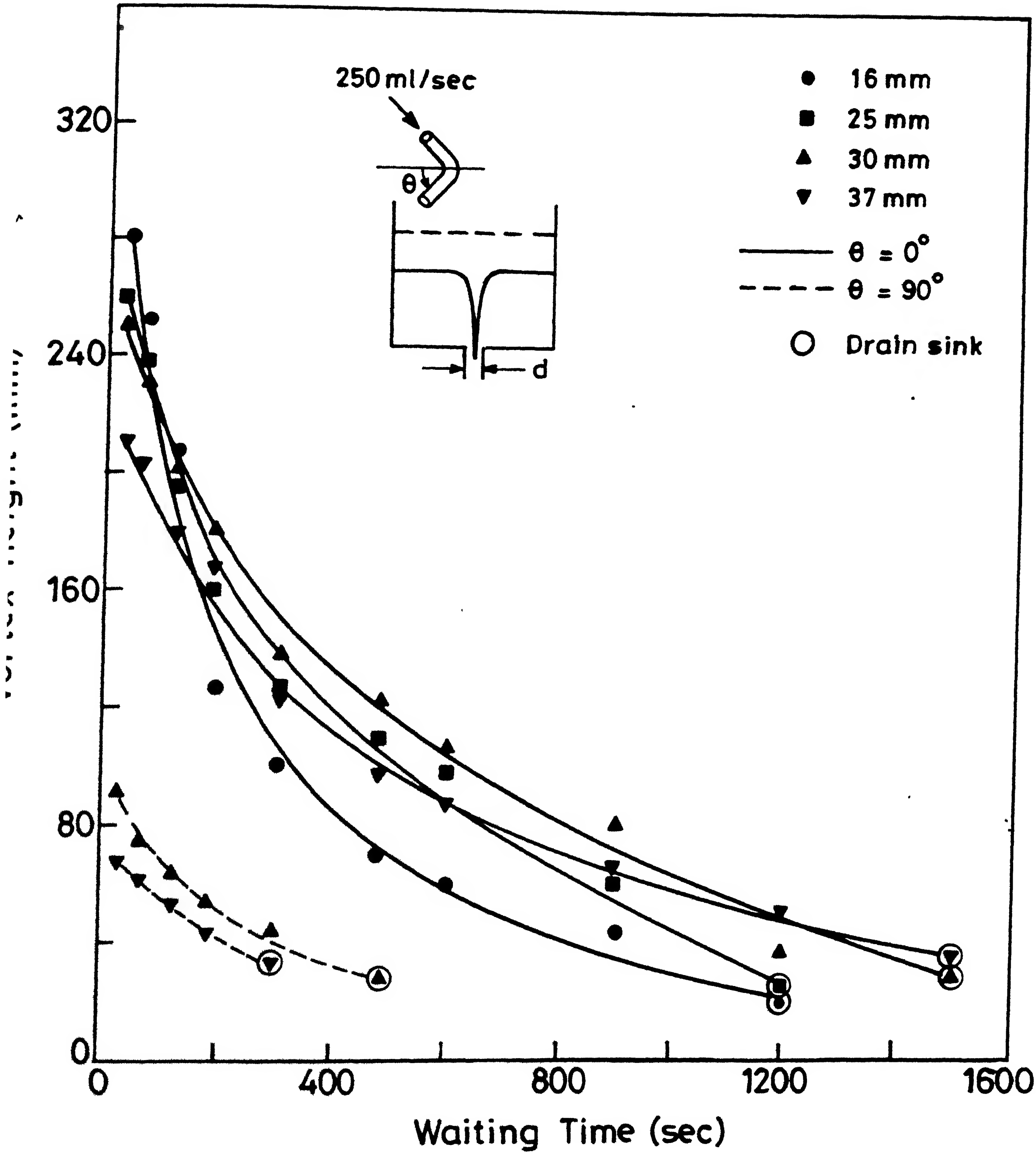


Fig.3.16 Effect of waiting time on Vortex height for different nozzle diameters

flow rate. But variation of the flow rate does not influence the vortex height much for waiting times above 300 sec. So it is decided to employ inlet flow rate of 250 ml/sec. in rest of the experiments.

For eccentric nozzles, it can be observed from the Fig. 3.15 that variation in the inlet flow rate does not effect appreciably vortex height. The variation in vortex height is not more than 25mm for all waiting time conditions.

It is also observed that vortex height for centric nozzles is considerably larger than that for the eccentric nozzles. But for waiting times greater than 900 sec. the variation in vortex height is not much appreciable. For 900 sec. waiting time there is no variation in vortex height for centric and eccentric nozzles except for the inlet flow rate of 377 ml/sec., the variation in vortex height is 10 mm. Initially when the bath is just filled, the rotational flow in the bath is stronger and oriented towards centre of the bath. For centric nozzles this favours the early vortex formation but not for eccentric nozzles. Therefore, at short waiting times a considerable difference in vortex height is observed for centric and eccentric nozzles. For large waiting times, the effect of initial rotational flow considerably decreases and discharging nozzle diameter causes vortex formation by creating circulatory flow during draining. So, there is not much difference in vortex height observed for centric and eccentric nozzles for long waiting times.

Waiting time effect on vortex height is studied for nozzle diameters above 30 mm in axial mode of filling.

For all the modes of filling and nozzle diameters the vortex height much smaller in axial model of filling than its counter part tangential mode. In the axial mode of filling no vortex is observed at waiting times beyond 480 sec for 30 mm nozzle dia and 30 sec for 37 mm dia no vortex is observed at or beyond 1500 seconds waiting time for tangential mode.

3.2.1.2 Effect of Mode of Filling on Vortex height

Fig. 3.17 shows the variation of vortex height as a function of inlet angle at different waiting times. It is observed that increasing the inlet angle decreases the vortex height. Vortex forms due to the cumulative effect of initial rotational flow and rotational flow created due to the outlet nozzle.

Increasing the angle of inlet decreases the initial rotational flow created due to the filling of the vessel. Initial rotational flow will be proportional to the cosine of the inlet angle. So, when the inlet angle is increased the initial rotational component decreases by a factor of Cos θ. For tangential mode of filling, the inlet angle is of zero degree and hence maximum initial rotational flows. When Cosine angle of the inlet is of 90° (i.e. axial mode of filling) almost no rotational flow is created by filling. For intermediate angles of the inlet nozzle, the initial rotational flow created by filling will be in between maximum and minimum values.

So when the mode of filling is tangential, the vortex forms due to the cumulative effect of initial rotational flow and rotational flow created by outlet nozzle. So, vortex height is maximum. For the similar conditions in axial mode of filling,

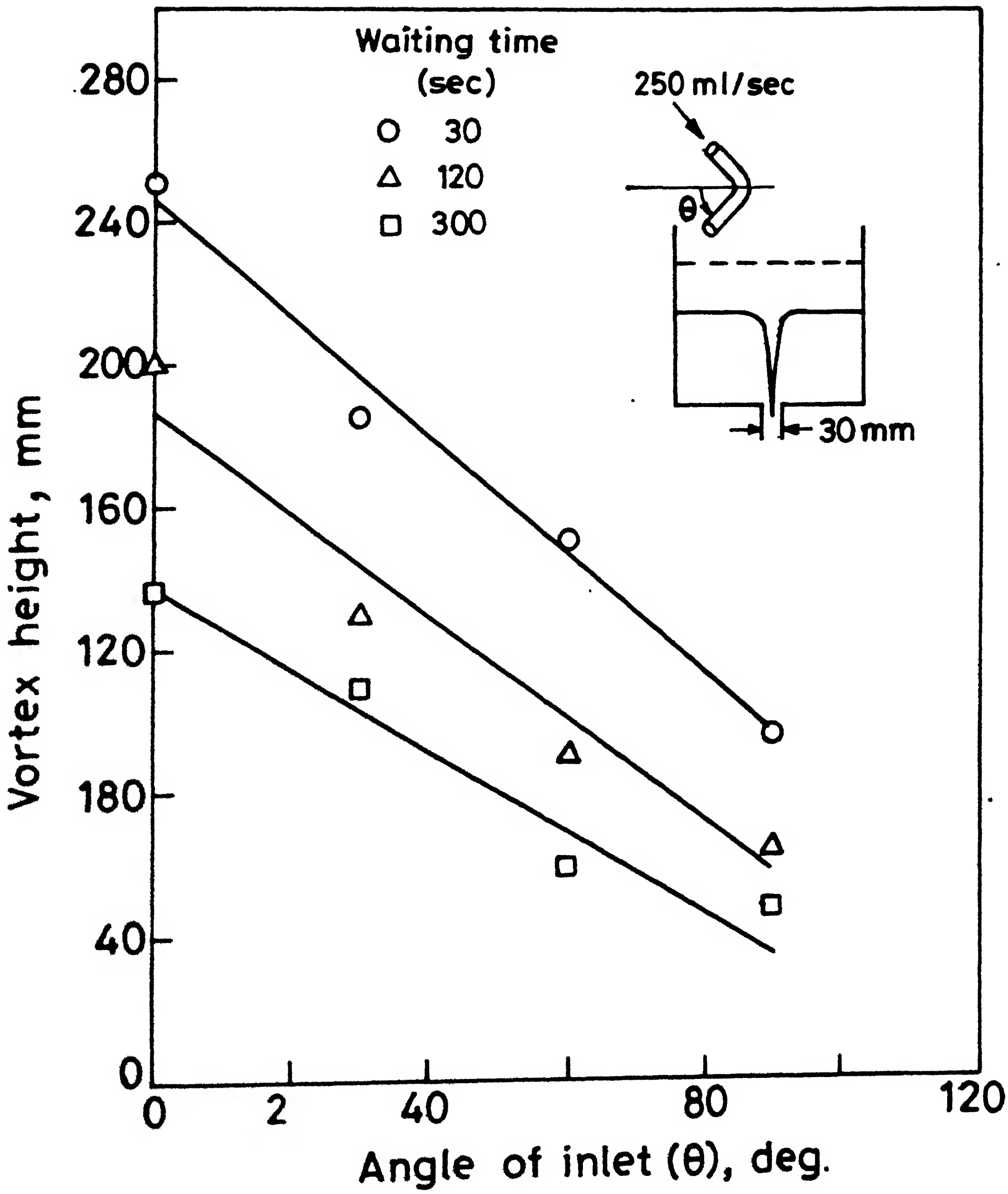


Fig.3.17 Effect of angle of Inlet on Vortex height at different waiting times

vortex forms mainly due to the effect of rotational flow created by outlet nozzle. So vortex height is minimum. For 30 sec. waiting time, the vortex height for tangential mode of filling is 250 mm and for axial filling, 95 mm. For intermediate positions of inlet nozzle angle the vortex height will be in between the maximum and minum values. So as the inlet angle increases, vortex height decreases.

3.2.1.3 Effect of Nozzle Diameter on Vortex Height

Effect of nozzle diameter on vortex height is studied for tangential and axial modes of filling of the vessel.

The Figs. 3.18 and 3.19 show the variation of vortex height as a function of diameter of the nozzle at different waiting times and off-central nozzle location.

Vortex formation is resultant of the effects produced by the waiting time and nozzle diameter.

Within the limits of nozzle diameters, vortex height decreases as the diameter increases for waiting times smaller than 120 sec. Whereas beyond 120 seconds nozzle diameter has a dual effect: vortex height increases with increase in nozzle diameter from 16 to 30 mm, beyond 30 mm the vortex height decreases. This observation can be seen in the figure 3.22 for all waiting times in between 180 seconds and beyond 1500 seconds. Beyond 1500 seconds no vortex formation has been observed for tangential mode of filling.

The above behaviour can be explained by considering the mechanism of vortex formation. it is known that vortex can form only when a certain particular value of RPM is reached. This

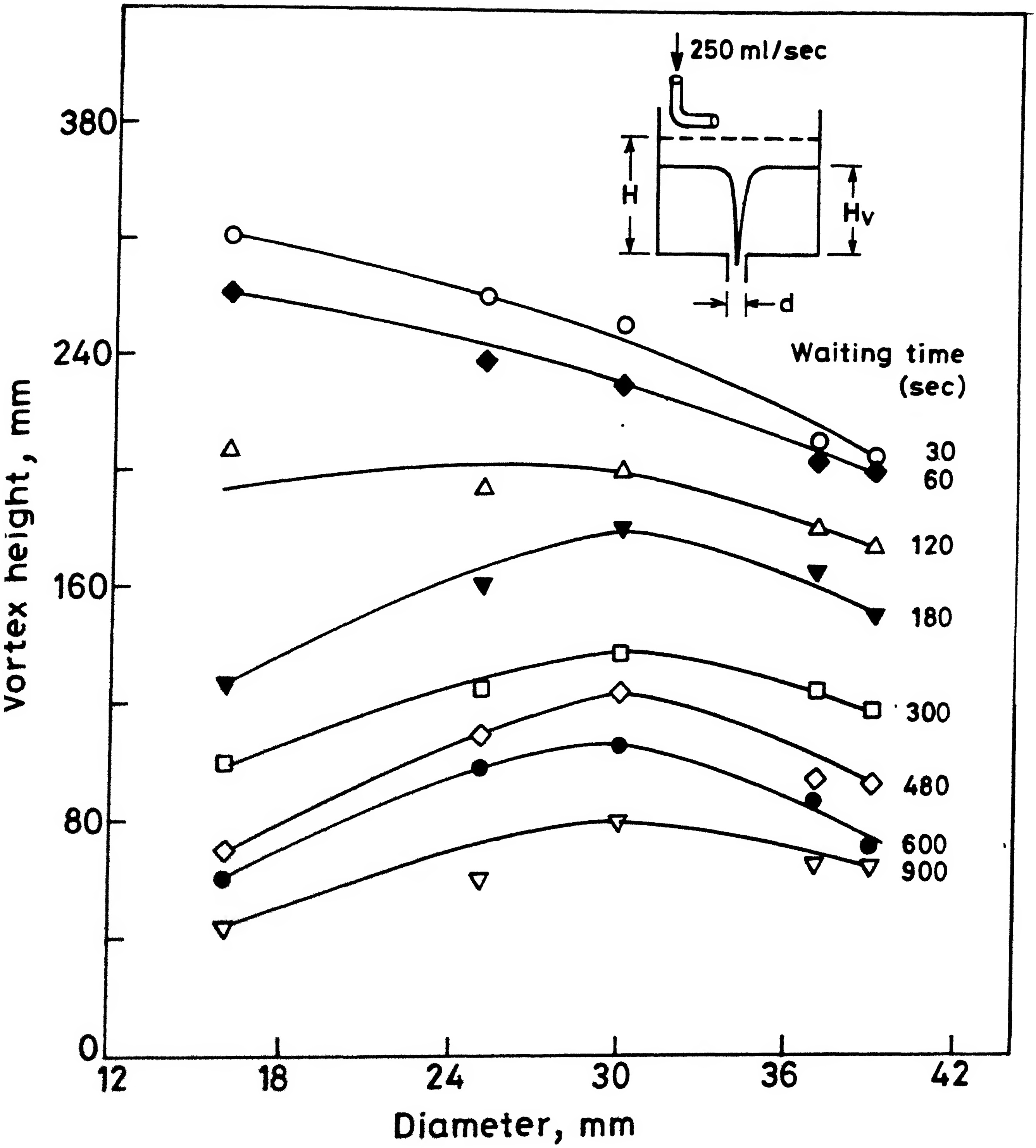


Fig.3.18 Effect of nozzle diameter on Vortex height at different waiting times

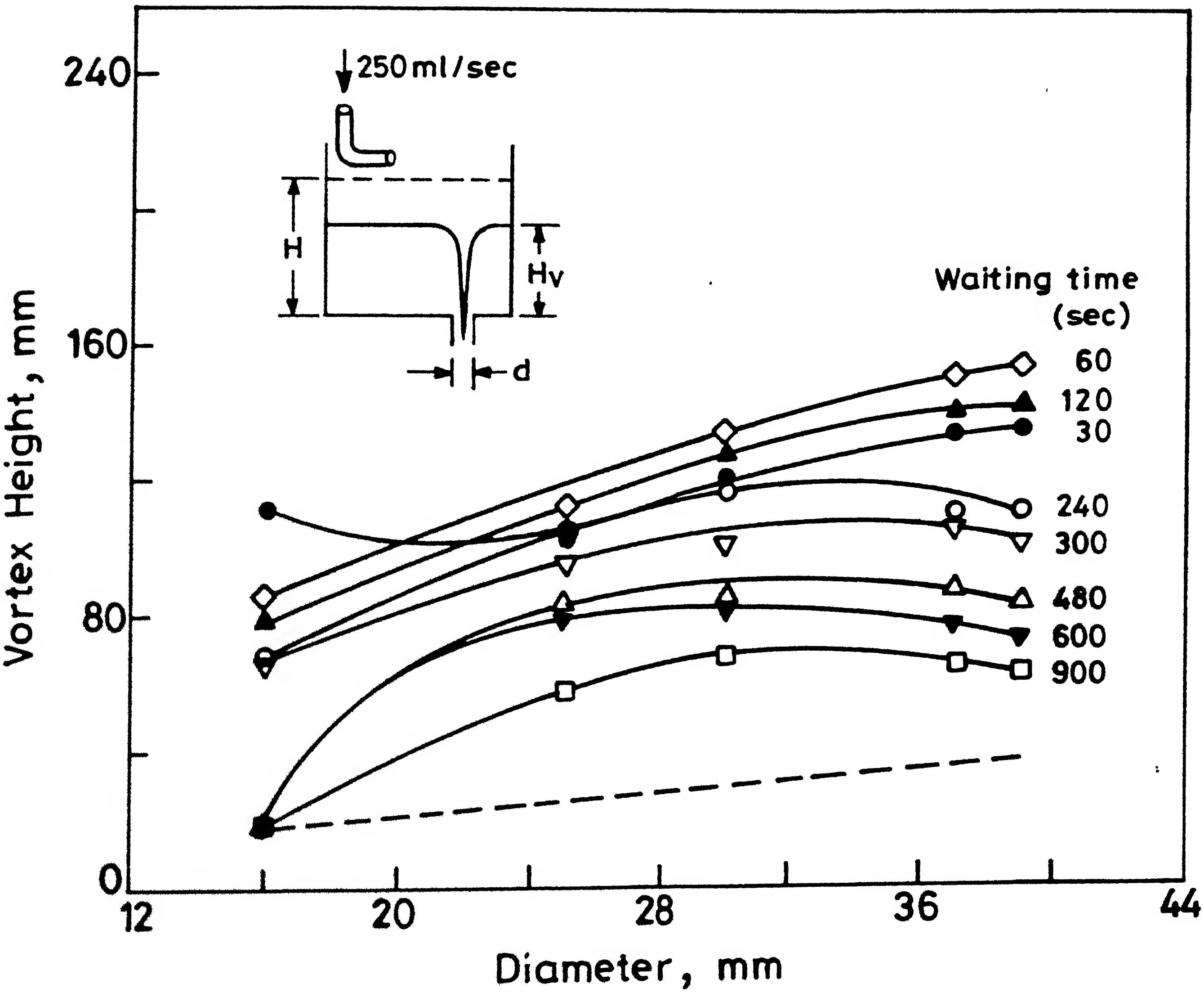


Fig.3.19 Effect of nozzle diameter on Vortex height at different waiting times

particular value can reach only for certain waiting time and diameter combinations. Within the limits of present study 1500 second waiting time and 16-39 mm diameter nozzle could not produce any vortex. At smaller waiting times the initial strong nozzle diameter rotational flow is strong but not sufficient to form vortex. The nozzle diameter contributes only to enhance this rotational flow to reach particular RPM. As the waiting time increases the effect of diameter on vortex formation is predominant and gives rise to the duel effect. In the present experiment maximum vortex height is observed at 30 mm nozzle diameter for waiting times in between 180 and 900 seconds. As the nozzle diameter increases from .16 to 30 mm the increasing vortex height is due to the increase in rotational flow created by increasing the nozzle diameter. In such a way that particular RPM is reached to cause the vortex.

Beyond 30 mm the decrease in vortex height is probably due to the fast increase in the volume discharge of water as compared to previous one. So by the time vortex forms the nozzle diameter beyond 30 mm are discharging more amount of water, so decrease in vortex height is observed.

The Fig. 3.19 shows the effect of diameter on vortex height at different waiting times. The inserted picture in the graph show the experimental conditions. For short waiting times (i.e. less than 120 sec), the vortex height increases with increasing diameter in the regime one. This is because of the fact that, initial rotational flow is oriented towards the centre of the bath, which is not favourable in vortex formation for eccentric

nozzles. With increase in diameter of nozzle the rotational flow created during discharge increases. This produces vortex of greater height with increasing diameter.

In the regime two, vortex height increases with increasing nozzle diameter.

In the third regime, the vortex height slightly decreases with increasing the diameter.

A similar reasoning that is given for centric nozzles in the regimes 2 and 3 can also be given for eccentric nozzles in regimes 2 and 3, to explain change in vortex height with diameter.

The variation of vortex height with diameter at different waiting times is given in Table 4 for axial mode of filling. From the table it can be seen that the nozzle diameter has the same type of variation as that shown in Fig. 3.18.

3.2.2 Vortex Time

Time of vortex formation is the time at which it forms just after opening the nozzle. The effects of diameter, waiting time and eccentricity on vortex time are studied.

3.2.2.1 Effect of Diameter

Figs. 3.20 and 3.21 show the variation of vortex time as a function of outlet nozzle diameter at different waiting times. The inserted picture in the figures show the experimental conditions.

It is observed that increasing the diameter decreases the vortex time for both the centric and eccentric nozzles. When the outlet is opened, the rotational flow is created in the vessel.

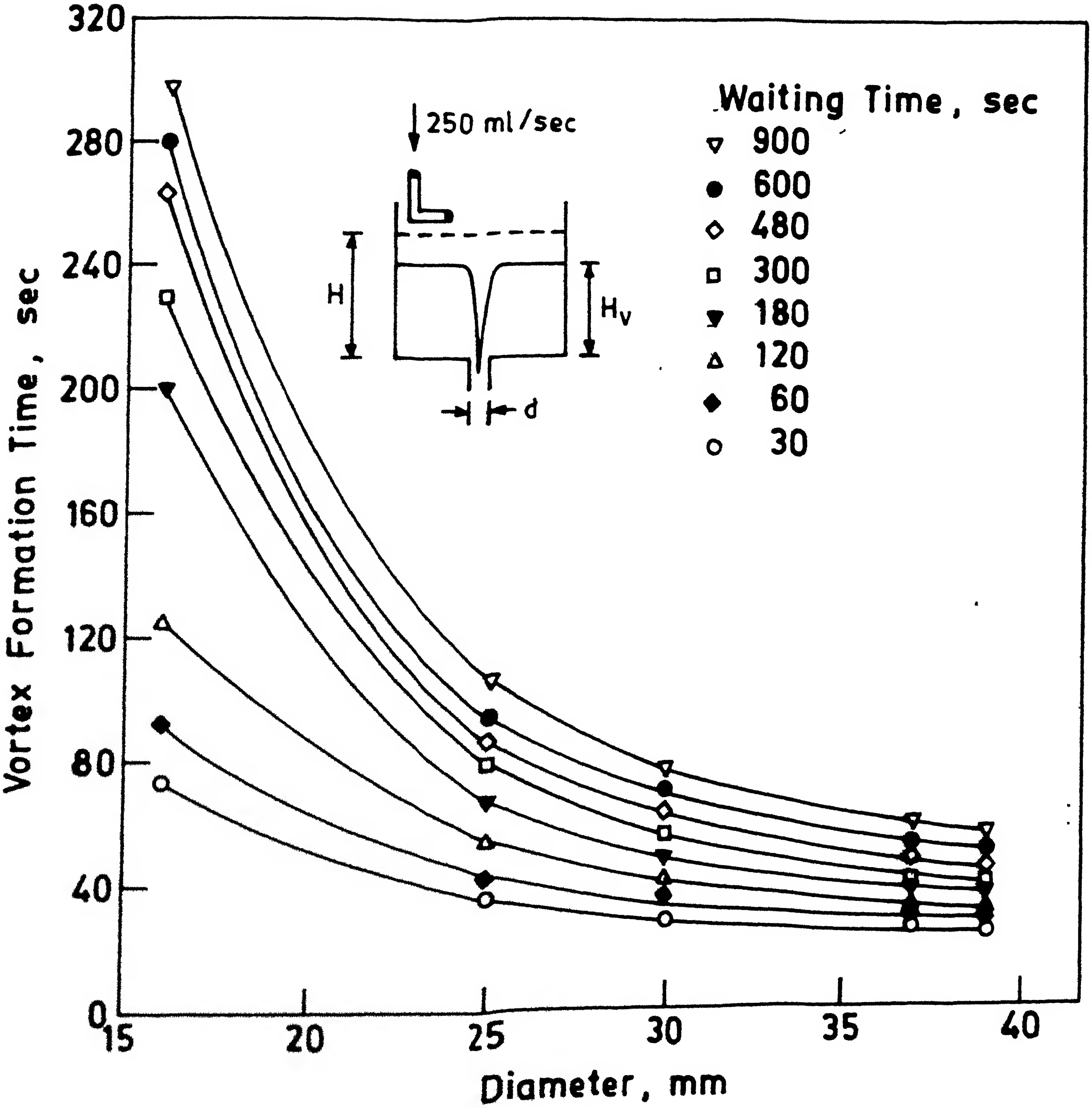


Fig.3.20 Effect of nozzle diameter on Vortex time at different waiting times

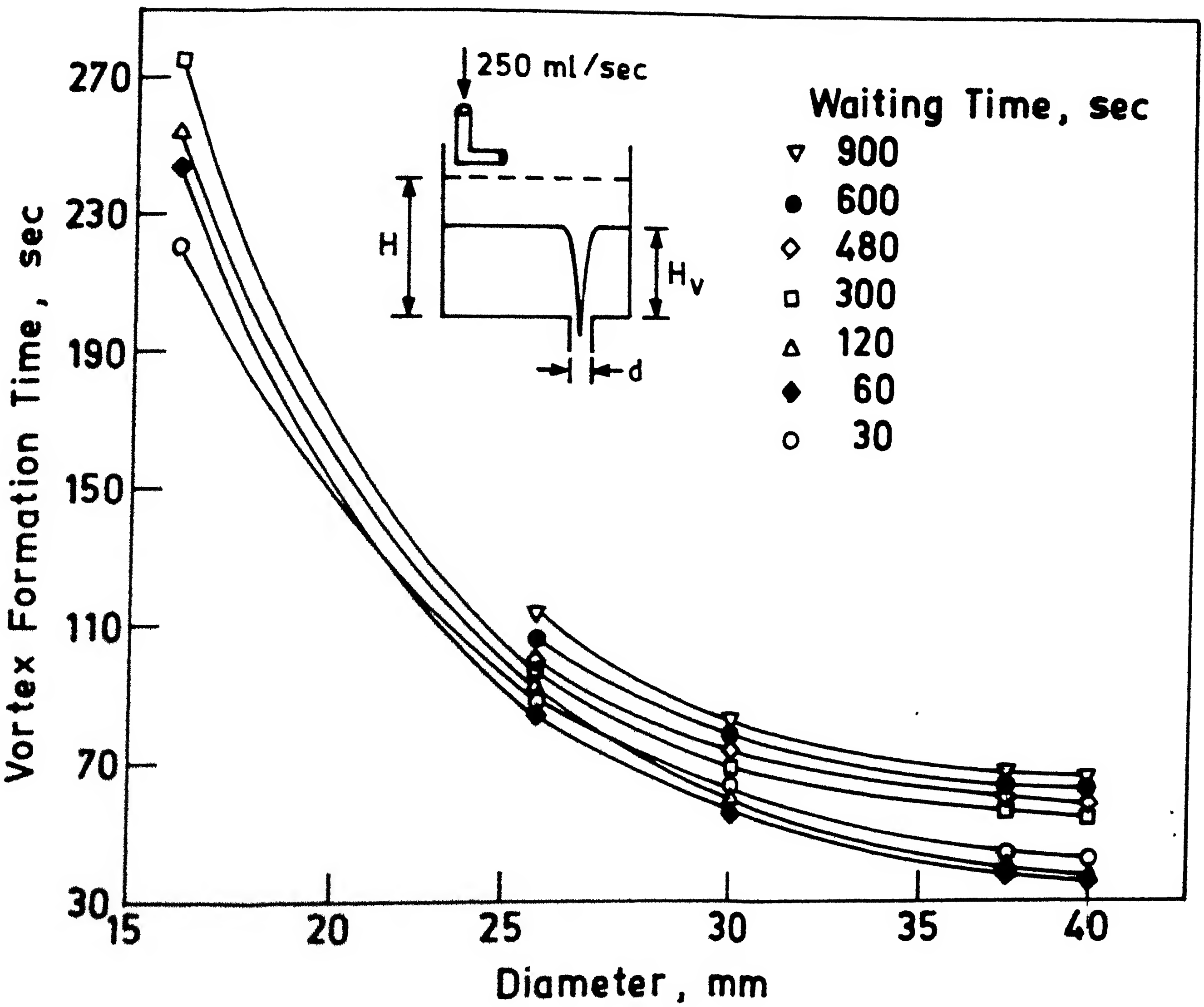


Fig.3.21 Effect of nozzle diameter on Vortex time at different waiting times

Increasing the nozzle diameter increases the rotational flow. This causes early reaching of critical rotational velocity at which vortex forms and hence, reduction in vortex time at large nozzle diamters.

It can also be observed from the figures that increasing the waiting time delays the vortex time. Under normal conditions there is always present some conventional flow with rotational component in the vessel. When the fluid moves to the outlet, this small initial rotation flow gets amplified due to conservation of angular momentum (Eq. 1.1).

Amplification of initial velocity will occur with a factor of $(\gamma_1/\gamma_2)^2$ when the particle reaches from γ_1 radius to γ_2 radius.

The waiting time given before the opening of nozzle reduces the initial rotational component in the vessel which is created by filling of the vessel. With decreasing the initial rotational velocity, the time taken to reach the critical velocity at which vortex forms is delayed. So, increasing the waiting time increases the vortex time.

It can also be observed from Figs. 3.20 and 3.21 that vortex time is considerably shorter for centric nozzles than that for eccentric nozzles. This means vortex time is delayed in eccentric nozzles. For eccentric nozzles the initial rotational flow in the bath is not favourable to form vortex because of the fact that rotational fow is oriented towards the centre. Thus, vortex time is delayed for eccentric nozzles.

3.2.3 Drain Sink

It is observed that at long waiting times vortex is not observed but a drain sink is formed at the end of draining process. It is also observed that drain sink formed is not effected by mode of filling, eccentric flow rate and waiting time. The height of the drain sink depends only on the diameter of the outlet. It is observed that increasing the outlet diameter increases the drain sink height.

Fig. 3.22 shows the variation of drain sink height as a function of outlet nozzle diameter. At the end of draining process the water remained in the vessel is not sufficient to fill the nozzle completely, so an aircore is developed at the centre of the nozzle without precedent of vortex. Increasing the outlet nozzle diameter increases amount of water required to completely fill up the nozzle. So drain sink forms earlier for bigger diameter nozzles, than for smaller diameter ones, which leads to increase in drain sink height with increase in diameter.

3.2.4 Drainage Curves

Vortex time and time to discharge the given amount of water are obtained from the discharge curves. Drainage curves prepared for each diameter of nozzle for different experimental conditions. Fig. 3.23 to 3.31 show the discharge curves. The inserted picture in figures show the experimental conditions. The curves passing through the hollow circles show drainage percentage. The other curves passing through the closed circles show variation of vortex time as a function of waiting time.

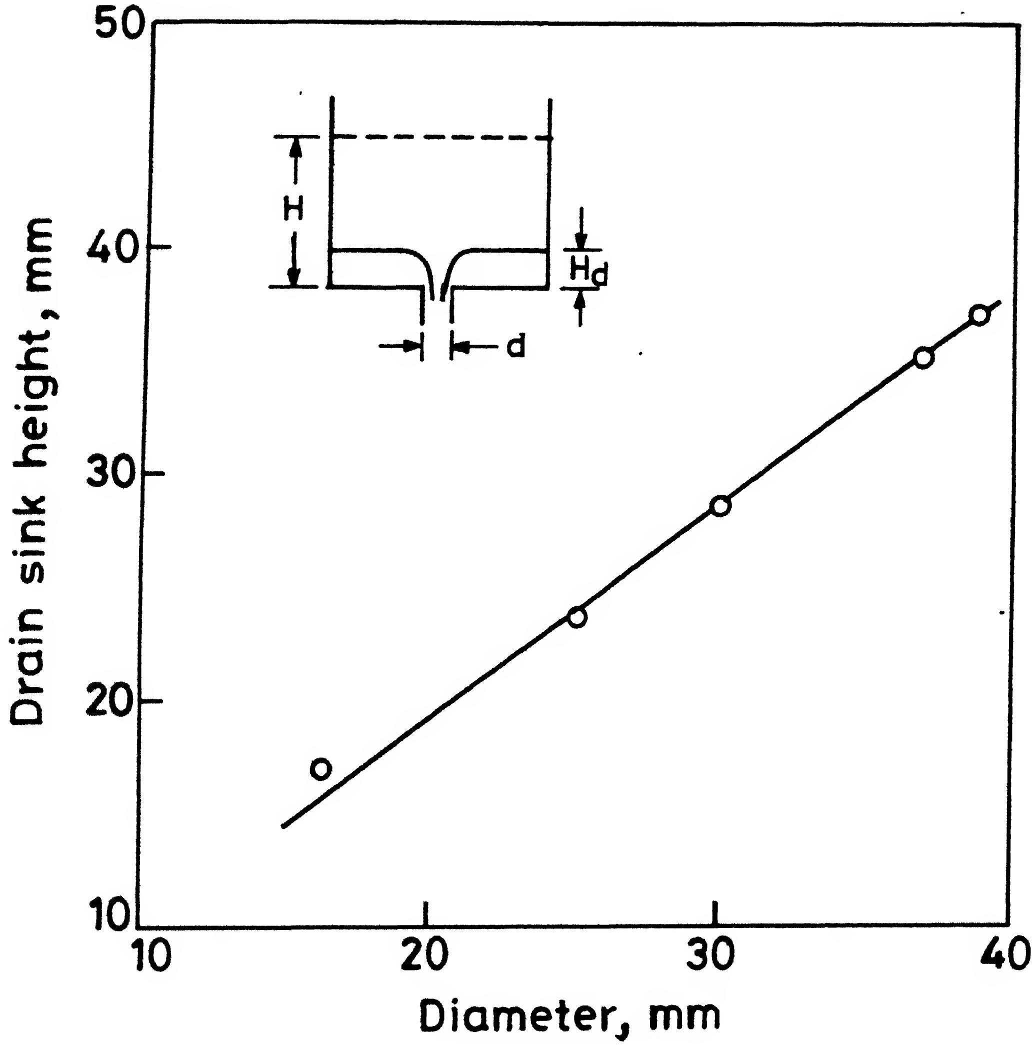


Fig.3.22 Effect of nozzle diameter on Drain Sink Height

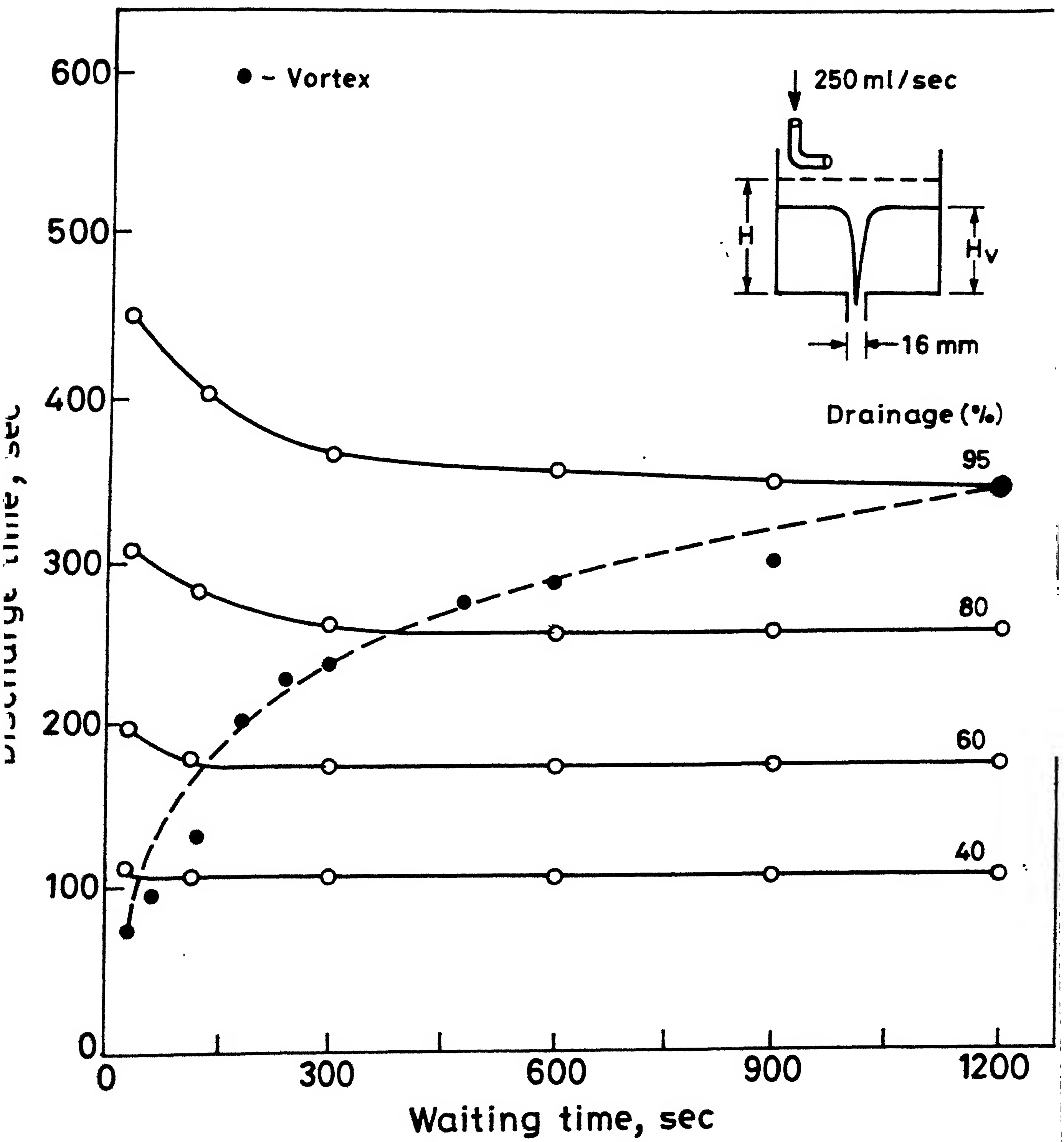


Fig.3.23 Drainage curve showing the discharge time as a function of waiting time. (The broken line shows the time of vortex formation.)

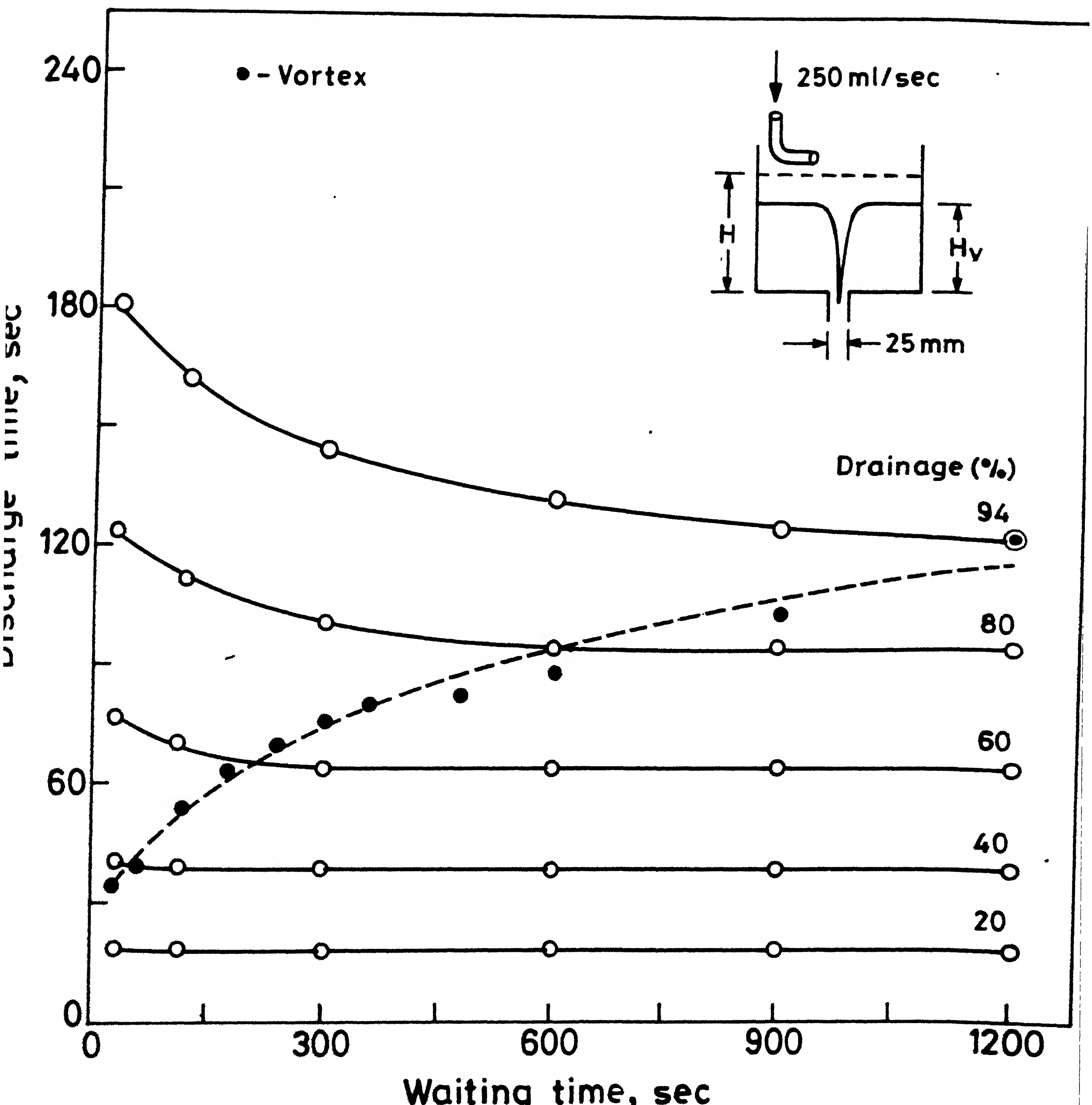


Fig.3.24 Drainage curve showing the discharge time as a function of waiting time. (The broken line shows the time of vortex formation.)

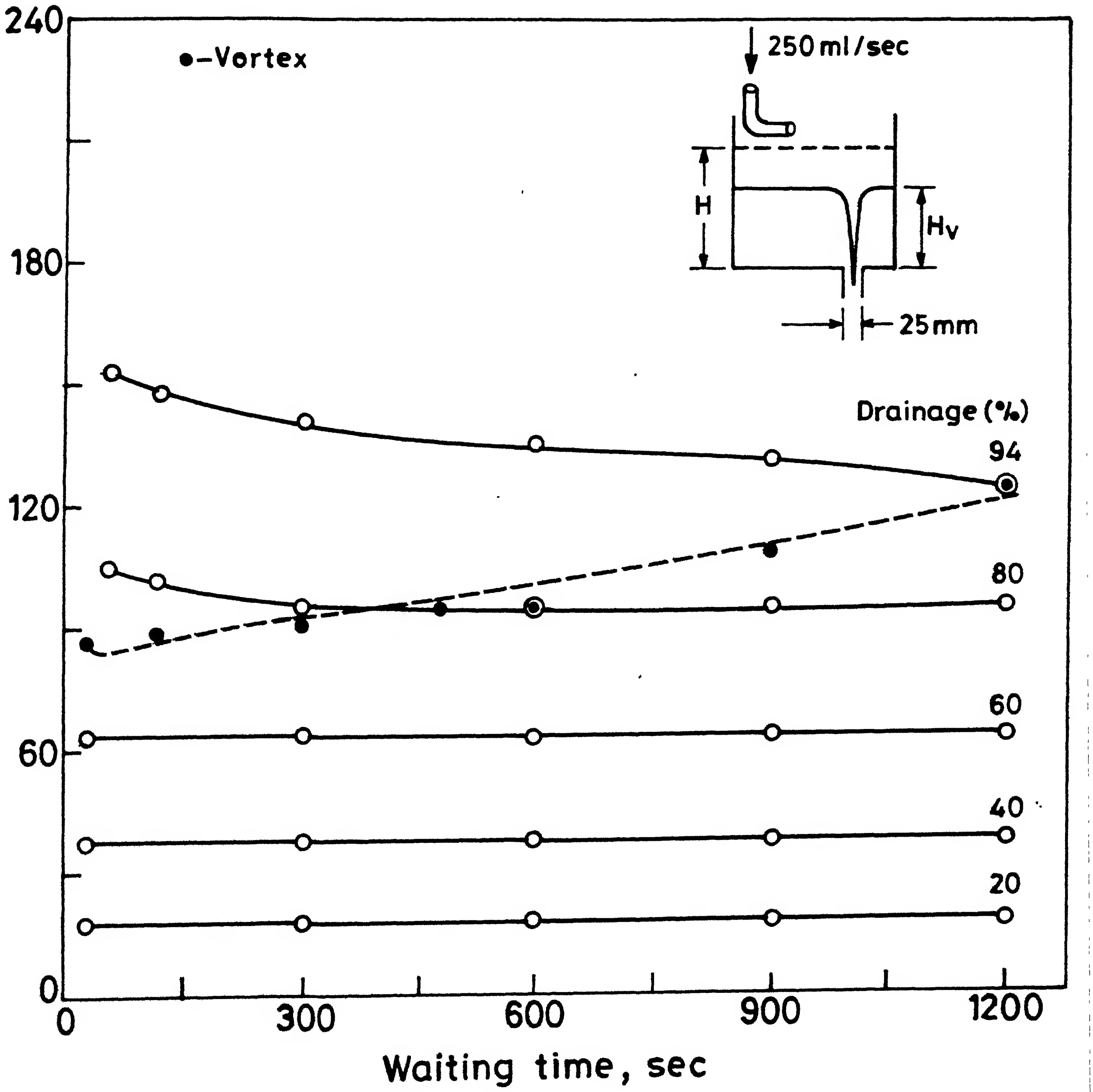


Fig.3.25 Drainage curve showing the discharge time as a function of waiting time. (The broken line shows the time of vortex formation.)

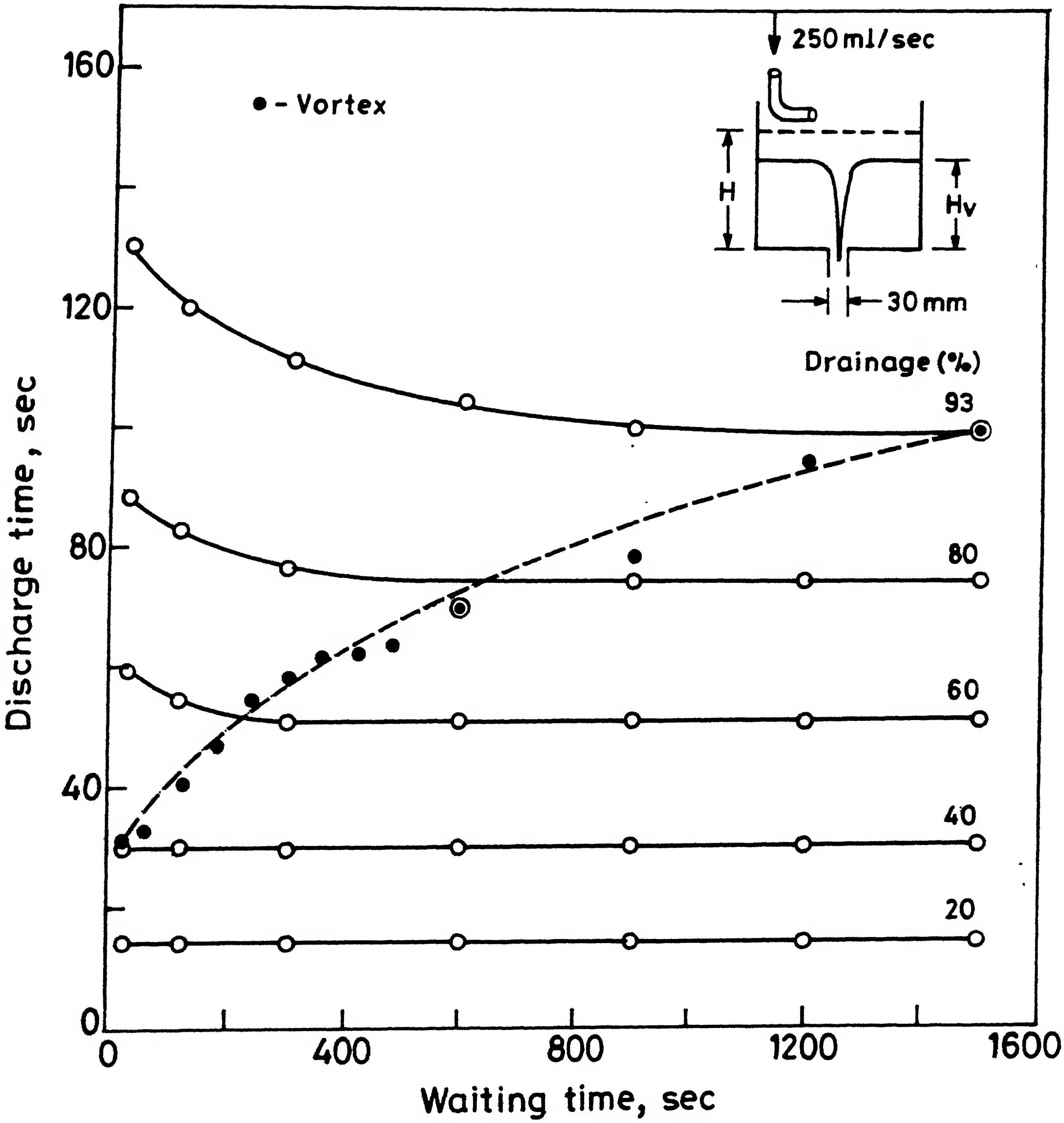


Fig.3.26 Drainage curve showing the discharge time as a function of waiting time. (The broken line shows the time of vortex formation.)

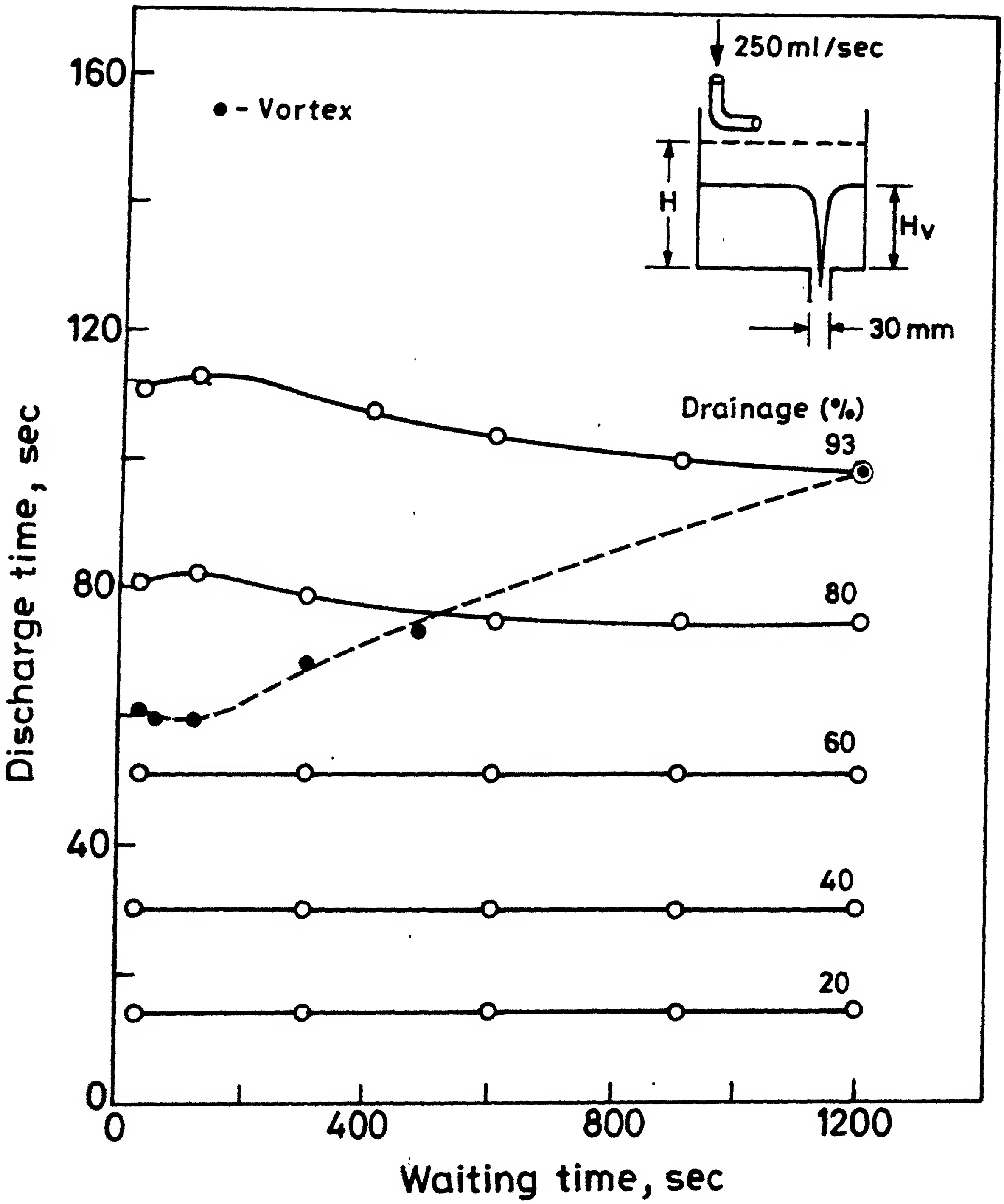


Fig.3.27 Drainage curve showing the discharge time as a function of waiting time. (The broken line shows the time of vortex formation.)

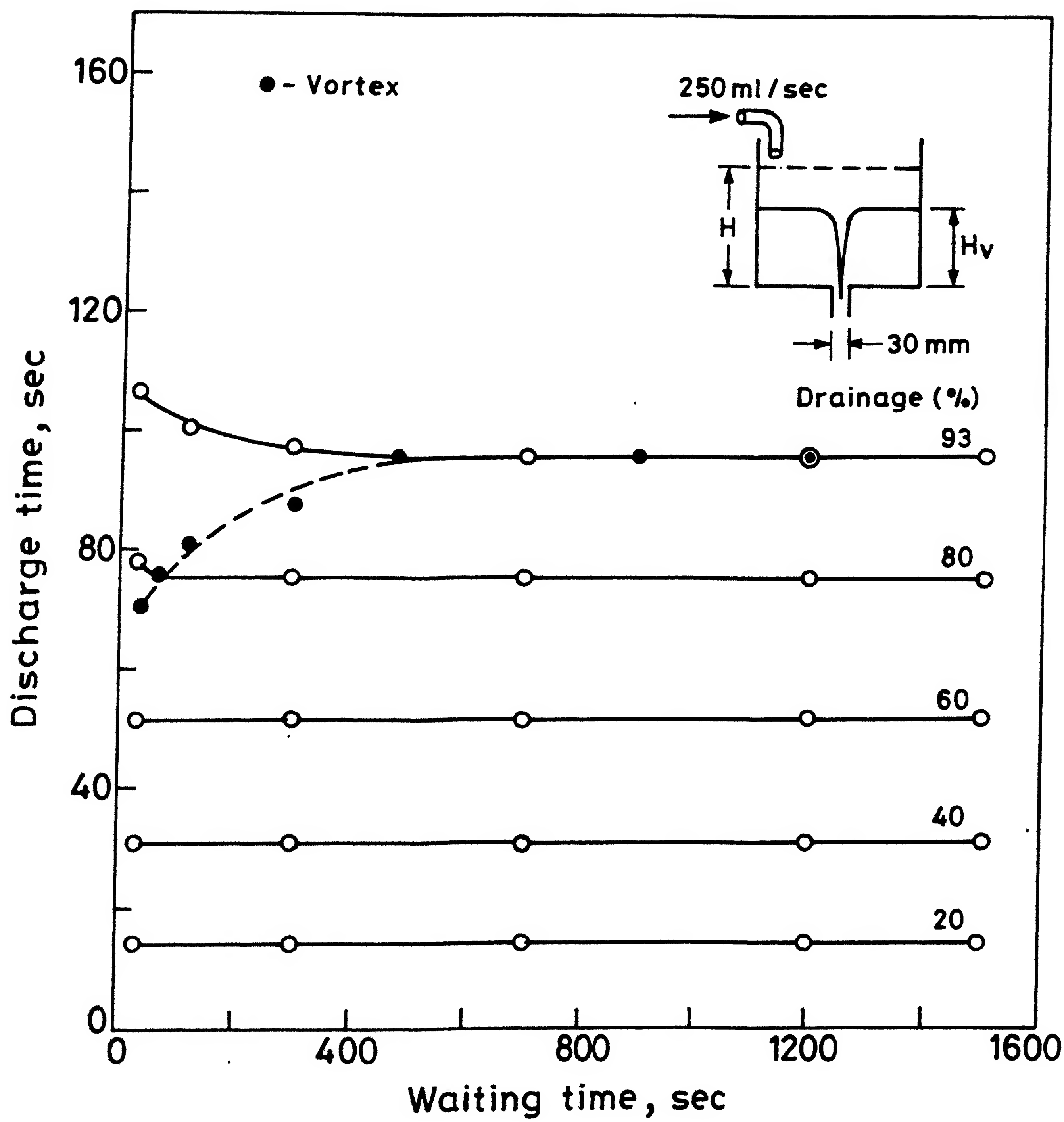


Fig.3.28 Drainage curve showing the discharge time as a function of waiting time. (The broken line shows the time of vortex formation.)

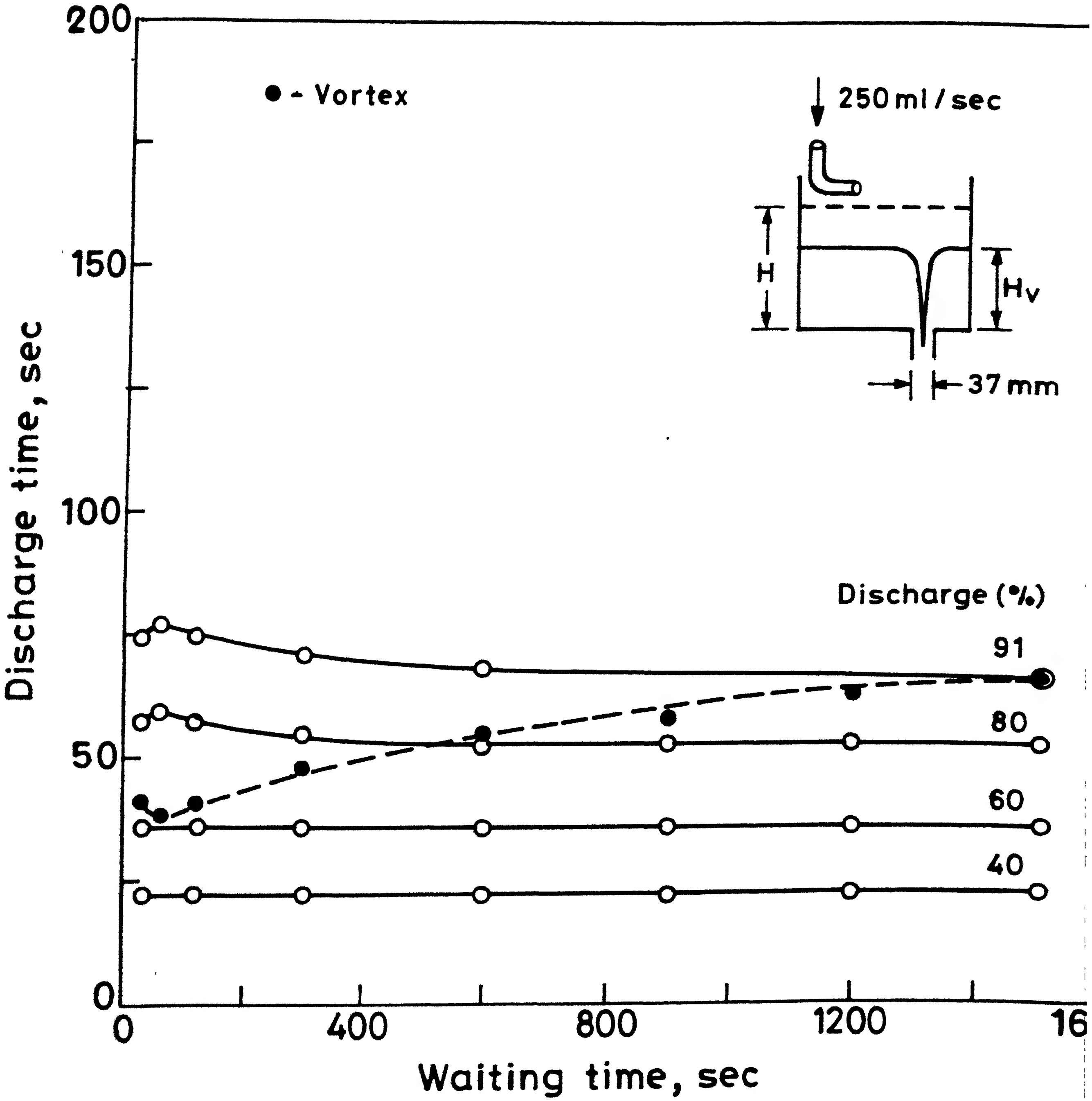


Fig.3.30 Drainage curve showing the discharge time as a func of waiting time. (The broken line shows the time vortex formation.)

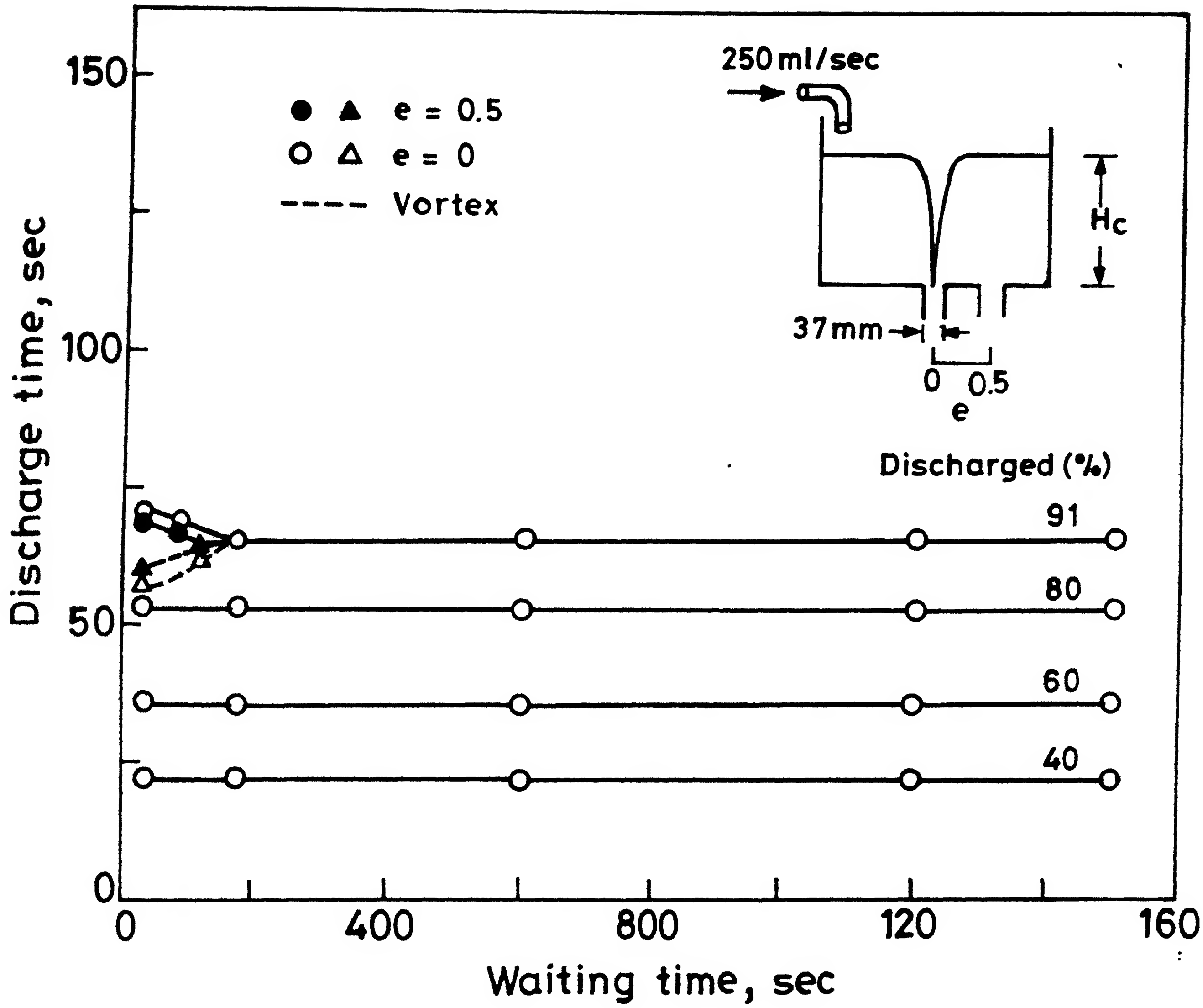


Fig.3.31 Drainage curve showing the discharge time as a function of waiting time. (The broken line shows the time of vortex formation.)

It is clearly evident that with increasing waiting time vortex develops later and drainage occurs faster. From these figures it can be observed that for given conditions the time of vortex formation can be obtained. This is to obtain information on discharge percentage of the liquid (i.e. without entrainment of air or light fluid). The waiting time given to discharge the particular amount of water without entrainment of air can be found from the figures.

With the increase in waiting time the vortex develops later and drainage occurs faster because when there is formation of vortex, air core passes through the nozzle, thus the effective nozzle diameter is decreased. So time to discharge the given amount is more when vortex forms than for no vortex cases.

3.3 Measurement of Rotational Velocity

When the bath is filled there is always some rotational velocity. When the outlet is opened the rotational flow increases due to the conservation of angular momentum.

To meausre the circulatory velocity a small float is left on the water level. The attempts to measure the rotational velocity when the bath is just filled without opening the outlet nozzle are failed. The float is not moving in a particular path, instead, it is moving disorderly because of surface waves. A steel wire is hanged from the top exactly above the nozzle to locate the centre while measuring the rotational velocity.

When the outlet is opened the float is carefully placed 2 cm away from the centre, the float starts revolving around the centre. The rpm is reasured at the time of vortex for different

diameters and for centric and eccentric nozzles. The results are tabulated in table (3.8).

It is observed that at the time of vortex formation the rotational velocity measured is almost same for all cases.

3.4 Measurement of Entrainment of Cyclohexane

Inlet flow rate 250 m lit/sec is used to fill the vessel upto the desired level. After filling the vessel 1.5 liters of cyclohexane is added to the top of the water. After a particular waiting time the outlet is opened. The diameter of the outlet is 16 mm. The discharged water is collected in measuring cups. When there is no vortex formation only water is drained through the nozzle. When the vortex forms the cyclohexane is drawn from the surface through the centre of the vortex.

The entrained cyclohexane is measured from the collected samples. The results are shown in table (3.9). These results show that amount of cyclohexane entrained is independent of the waiting time. The entrained cyclohexaned measured in a 1 lit. jar for 30 sec, 60 sec experiments is 10 ml. It is also observed that the entrained cyclohexane in first four samples is same and in the fifth sample a slightly less. This is because the cyclohexane is carried from the centre of the vessel into the nozzle through the aircore developed. Aftor the vortex formation at the centre, the cyclohexane is depleted after some time so in the last sample of the experiments contain slightly less amount of cyclohexane.

3.5 Regression Analysis

Experimental results have indicated that there is a continuous decrease in the vortex with height the increase in

diameter for waiting times less than 120 seconds. This behaviour is attributed to shorter waiting times.

At these shorter waiting times the effect of initial rotational flow created by the filling is predominant and the effect of diameter to enhance the rotational flow is relatively insignificant. This means that particular value of RPM required to form Vortex is reached mainly by the rotation induced in the bath by filling.

With the increase in waiting time, the intensity or rotational flow induced by filling decrease and the effect of diameter plays the role to produce the required RPM for the vortex formation. Experimental results have shown that a vortex height is maximum at 30 mm for all waiting times between 180sec to 1500sec. The maximum can be explained as follows. The instantaneous discharge voluem of water through the nozzle is given by

$$Q_1 = A \times V_i = A \sqrt{2gh_i} = \frac{\pi}{4} D^2 \sqrt{2gh_i} \qquad 3.1$$

If we decrease or increase the diameter of the nozzle say by $\pm$ 14mm from the referred 30mm then the instantaneous ratio of discharge according to the equation 3.1 is

$$\left[\frac{Q_{16}}{Q_{30}}\right] = 0.28 \qquad \left[\frac{Q_{30}}{Q_{30}}\right] = 1$$

and

$$\left[\frac{Q_{44}}{Q_{30}}\right] = 2.17$$

On comparing these values with Q_{30}/Q_{30}, we get the discharge

due to decrease in diameter is 0.72%, the discharge of 30mm. By increasing the value from 30 to 44 mm, the increase in discharge is 117%.

With this consideration we can explain the experimental observation of influence of diameter of nozzle on vortex height. For waiting times in between 180 seconds and 1200 seconds for centric and eccentric position of the nozzle.

Increasing the diameter increases the rotational flow induced by mode of filling.

Increasing the nozzle diameter beyond 16mm, upto 30mm increases the discharge rate but at the same time rotational flow created during discharge also increases, which mainly will cause vortex formation. So vortex height increases with increasing the nozzle diameter upto 30mm. Increasing the nozzle diameter beyond 30mm, increases the discharge rate fastly (compared to the previous). Although rotational flow created during discharge increases, the discharge through the nozzle diameter is predominant because of higher discharge rates.

Before the vortex formation, the bigger diameter nozzles discharges more amount of water. So vortex height decrease with increasing the nozzle diameter beyond 30mm.

In view of the above discussion the following type of correlations are developed.

Tangential Mode of Filling

For waiting times below 180 seconds for central and off-central nozzle locations.

$$\frac{H_V}{H_I} = C\ W\ T^m\ D^p \qquad 3.2$$

For waiting times between 180 seconds and 1200 seconds for central and off-central nozzle locations.

$$\frac{H_V}{H_I} = (a_o + a_1 D + a_2 D^2)\ W\ T^m\ Fr^n \qquad 3.3$$

Axial Mode of Filling

For axial mode of filling the function 3.3 is used.

Coefficients in equations 3.2 and 3.3 are presented in table 3.11.

Using the correlations developed, vortex height is calculated. The calculated vortex height is compared in Fig. 3.32 with the experimentally determined vortex height (see Figures 3.20 and 3.21). The comparison shows that the correlations describes well the vortex height.

In the literature no such correlations are available with which the values of the exponents of waiting time, and diameter could be compared. According to hydraulic researchers, it is qualitatively mentioned the duel roll of diameter on vortex. Vortex height increases first with increase in diameter.[9] According to Hammer Schimid et al. there is continuous decrease in vortex height with increase in diameter. They do not mention about the waiting time. It is expected that their results are valid for small waiting times.

3.6 Prediction of Vortex Time

Prediction of Vortex time is important from operational point of view.

Vortex time is predicted from the vortex height as follows.

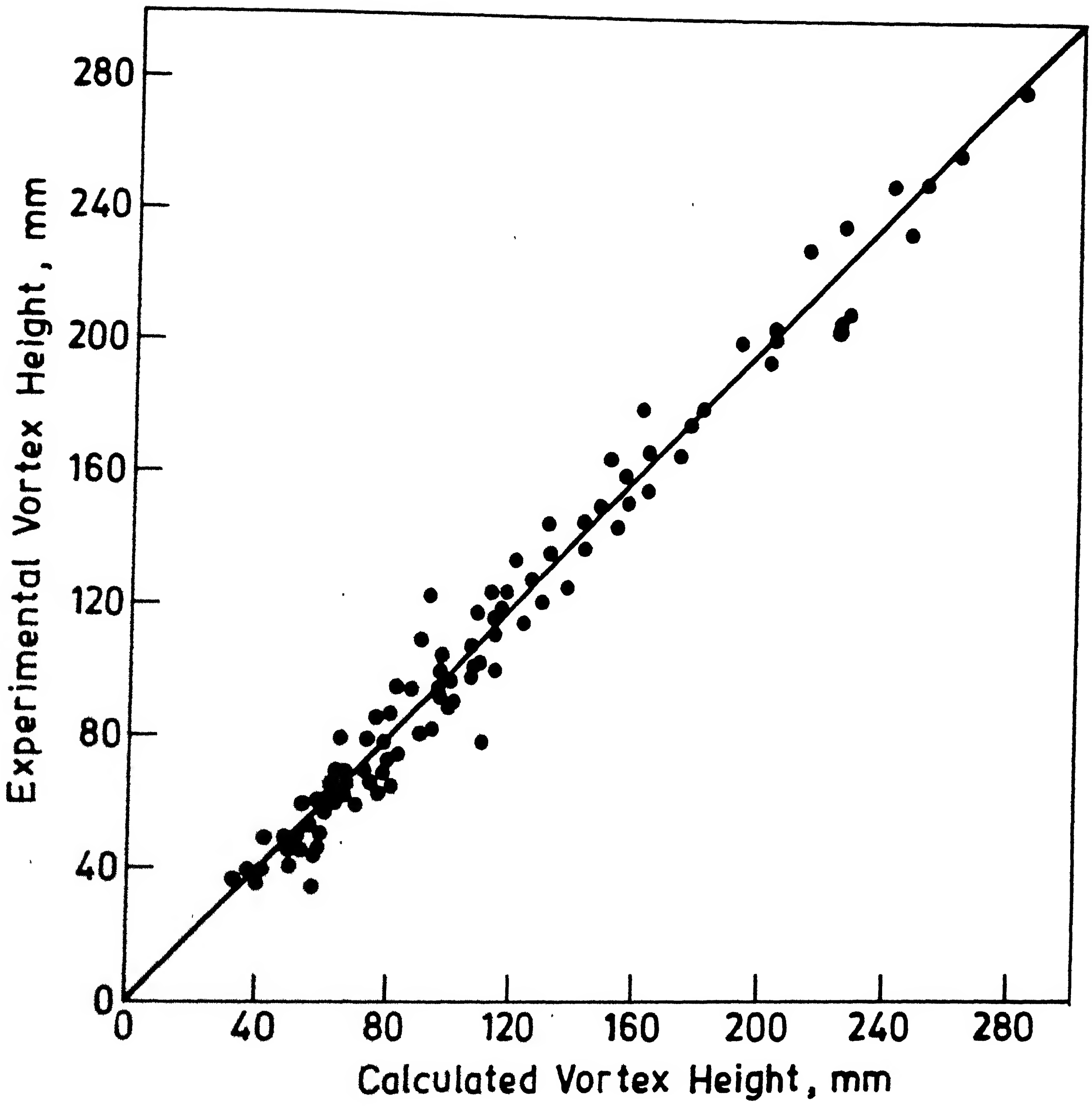


Fig.3.32 Comparison of the calculated and measured values of Vortex height

By applying the equation of continuity and energy, on macroscopic scale the following equation is obtained to determine the time for emptying the vessel through a nozzle located at the bottom. (The derivation of this equation is given in Appendix A-1)

$$t = \sqrt{(1 + 4f \frac{L}{D})} \frac{A_V}{A_N} \sqrt{2H_I/g} \; (1 - \sqrt{H_f/H_I}) \qquad 3.4$$

When the final height becomes vortex height, time becomes vortex time.

$$t_V = \sqrt{(1 + 4f \frac{L}{D})} \frac{A_V}{A_N} \sqrt{2H_I/g} \; (1 - \sqrt{H_f/H_I}) \qquad 3.5$$

To predict the vortex time for the given conditions, corresponding regression function is used in equation 3.5. Fig. 3.33 shows the comparison of vortex time calculated from equation (3.5) and experimental vortex time.

It can seen from the graph that vortex time predicted by equation (3.5) matches well with the experimental vortex time.

3.7 Suppression of Vortex Formation

Vortex formation can be suppressed by dampening the rotational velocity in the bath. Flow obstacles, lighter liquid than water of various viscosities are used for suppresion of vortex formation. Results are presented in Table 3.10. When the solid thermocol sheet is used to cover the top surface, no vortex is observed, even the initial rotational flow when the nozzle is opened is very strong. When paraffin oil of different viscosities is added to the water, it is observed that vortex height is slightly lower than that for no paraffin experiments.

Flow obstacles experiments have also shown that, vortex height is lower than that for no flow obstacles experiments.

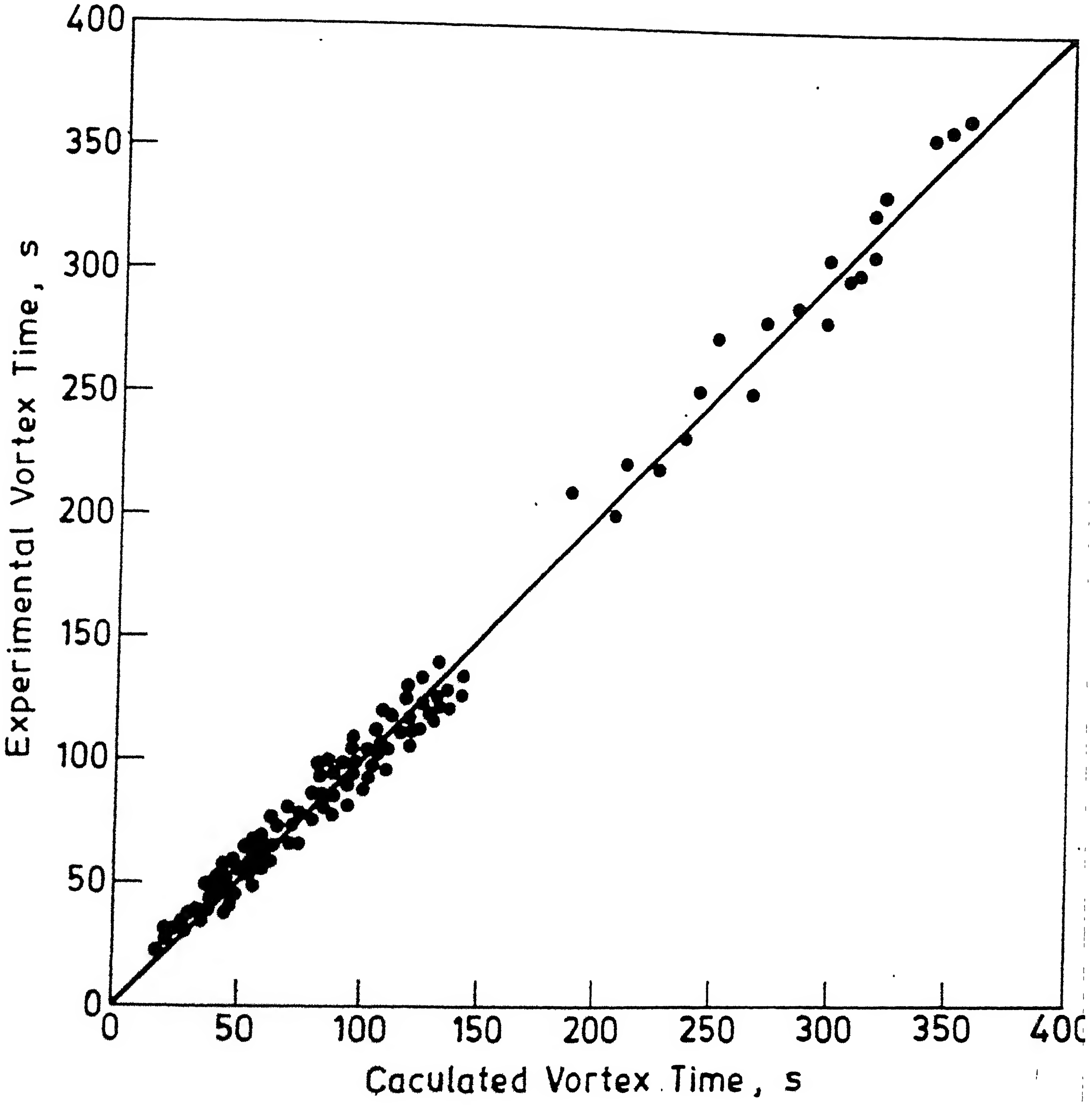


Fig.3.33 Comparison of the calculated and measured values of Vortex time

3.8 Industrial Applications

During steelmaking molten steel in presence of slag cover is transferred from primary steel making furnace (BOF or EAF) to the ladle and to the mould (in ingot casting) or ladle to tundish to mold in continuous casting. From the furnace to the ladle molten steel is transferred by tilting the furnace which simulates approximately the tangential mode of filling. In the subsequenct transfer operations molten steel is fed vertically into the vessel. This corresponds to axial mode of filling.

In each transfer operation it is important that slag should not be carried over. For this purpose a knowledge of vortex height or time should be of considerable use, for ladle change-over management or planning.

The vortex height is correlated with nozzle diameter, waiting time, inlet flow rate, inlet diameter for different modes of filling.

According to hydrodynamic researchers[10,11] vortex phenomena is not significantly influenced by surface tension, viscosity while draining the newtonian type of fluid. (Water and steel are both newtonian fluids, moreover the kinematic viscosity of water is 1.0 centistokes and for steel it is 0.91 centistokes.

From the above discussion it has been thought to use the present correlations to predict the vortex height for the industrial scale molten steel transfer operations.

The following typical data are used.

1) During the sequence casting tundish acts as a reservoir for the supply of molten steel to the continuous casting mold.

In this connection it is necessary to syncronise the ladle change over Period with the time for vortex formation during draining of molten steel from tundish to mold. For this purpose the correlation (3.3) may be used to predict the vortex height and from equation (3.5) vortex time can be calculated. In one particular 6 strand continuous billet casting, molten steel enters into each mold through 15mm nozzle diameter. The ladle stream diameter is 45mm. Steel flow rate is given as 220 l/min from tundish to all six moulds. From these data the Froude Number is calculated to be 12.04.

From these data the vortex height in tundish during ladle change-over period can be determined. Substituting the values into correlation 3.3 we get

$$\frac{H_V}{H_I} = 0.2919\ W\ T^{-0.25} \qquad 3.6$$

2 Tapping of molten steel from BOF to Ladle, is approximated to tangential mode of filling. Assuming ladle nozzle location is off-centre. In one particular plant the ladle nozzle diameter is 45 mm, flow rate from the ladle is 220 l/min. Assuming the off-central nozzle position vortex height can be calculated. Substituting the values into correlation 3.3, we get H_I = 266.35 cm.

$$\frac{H_V}{H_I} = 5.18 \times W_T^{-0.56} \qquad 3.6$$

Vortex height is calculated as a function of waiting time and given in Table 3.12

CHAPTER FOUR

CONCLUSIONS

A cold model study is carried out to study the phenomenon of vortex formation during drainage of metallurgical vessels. Two separate electrical circuits were employed to continuously record the decrease in height of water in the model vessel and to detect the vortex formation respectively. The following conclusions are drawn from the study.

1. The vortex height and time are function of mode of filling of vessel, nozzle diameter, inlet flow rate, location of nozzle and waiting time.
2. The vortex height is much less for axial mode of filling as compared to that for tangential mode of filling.
3. When the vessel is drained through eccentric nozzle vortex height is very much decreased.
4. It is observed that increase in diameter up to 30 mm increases the vortex height, but beyond 30 mm vortex height decreases.
5. It is observed that increase in waiting time decreases vortex height in all the cases studied in the present investigation.
6. Flow obstacles can delay the vortex formation
7. The correlations developed for predicting the vortex height have been applied to the actual metallurgical vessels. The calculated and the observed values of vortex height are found to be comparable.

SUGGESTIONS FOR FURTHER WORK

The further work may be done along the following lines:

1. The rotational flow in the bath during draining seem to be an important aspect for vortex formation. Rotational velocity can be measured during draining as a function of waiting time at different locations.
2. Flow obstacles seem to be good vortex suppressors. Optimum design of flow obstacles can be found out which completely eliminates the vortex formation.
3. Instruments can be developed to detect vortex and measure the level of liquid in high temperature work.
4. In the present investigation only one off-centre nozzle location is used. Experiments can be done for different eccentric nozzle locations and correlations can be found out between vortex height and eccentricity.

REFERENCES

1. A.W. Cramb, Transactions of the ISS, December 1988, I & SM, pp.39-48
2. E. T. Turkdogan, Ironmaking and Steelmaking, 1988, Vol 5, No. 6, pp.311-317
3. Albert Vander Heiden et al, Proceeding of 5th International Iron and Steel Conference, AIME, Washington, 1986, Vol.6, pp.755-760
4. Hammer Schimid et al, Ironmaking and Steelmaking, 1984, Vol.11, No. 6, pp. 332-339.
5. Hans-Jurgen et al, International Conference Secondary Metallurgy, 1987, pp. 149-159
6. Rolf Steffen et al, International Conference Secondary Metallurgy, 1987, pp.97-118
7. A. H. Shapiro, nature, 1962, 196, pp. 1080-1081
8. A. M. Binnie, J. mech. Engg., 1964, 6, pp. 256-257
9. Paul et al., J.H.D.,Hyz, May 1968, pp. 745-752
10. Larry Daggett et al, J.H.D. Hyz., Nov. 1974, pp.1565-1581
11. Merwin Sibulkin et al, J.H.D. Nov. 1974, HY 11, pp.1565-1579
12 Enzo Levi, ASCE National Hydraulic Engineering Conference, July 1990, pp.399-412

TABLES

Table 1 :Calibration of Millivolts in terms of Water Height in the bath

Water Height cm.	m.v.
40	10.8
39	10.6
38	10.3
37	9.8
36	9.4
35	9.2
34	8.9
33	8.6
32	8.3
31	8.1
30	7.8
29	7.6
28	7.4
27	7.1
25	6.8
24	6.6
22	6.6
18	5.7
16	5.45
14	5.2
10	4.8
8	4.6
6.5	4.5
5.8	4.4
4.6	4.3
2	4.23
1.8	4.20

Table 3.1:Vortex height for different Inlet Flow rates at different waiting times. Nozzle diameter - 25mm, Mode of filling -Tangential

(a) Central Nozzle

Waiting time (sec)	Flow Rate - ml/sec		
	178	250	377
30	245	260	287
60	230	238	250
120	180	195	225
180	150	160	180
300	140	149	160
400	115	125	145
600	103	118	130
900	50	60	75
1200	23	23	45
1500	23	23	23

Table 3.2: Vortex height for different Inlet Flow rates at different waiting times. Nozzle diameter - 25mm, Mode of filling -Tangential

(a) Off-central Nozzle

Waiting time (sec)	Flow Rate - ml/sec		
	178	250	377
30	95	100	105
60	110	108	130
120	98	98	105
300	95	94	90
400	80	80	90
600	78	80	80
900	80	60	65
1200	23	23	45

.e 3.3: Vortex Height (mm) for different nozzle diameters (mm) at different Waiting times (sec)

a. Mode of Filling - Tangential   Centre Position of Nozzle

:ing :ime / ·r	30	60	120	180	300	400	600	900	1200	1500
	280	252	207	126	100	70	60	44	18	18
	260	238	195	160	125	110	98	60	23	23
	250	23	200	180	137	124	106	80	35	28
	210	205	180	165	124	95	87	65	50	35
	205	202	175	147	118	95	70	60	50	37

le 3.3: Vortex Height (mm) for different nozzle diameters (mm) at different Waiting times (sec)

b. Mode of Filling - Tangential Off-Centre Position of Nozzle

ting time / er	30	60	120	180	300	400	600	900	1200
	111	86	80	68	65	18	18	18	18
	100	108	100	90	90	80	68	50	23
	120	135	130	118	100	85	80	68	28
	130	150	140	110	105	85	75	65	35
	135	153	145	110	100	70	70	62	37

Table 3.4 : Vortex Height (mm) for different nozzle diameters (mm

different Waiting times (sec). Mode of filling - Axial

(a) Central Nozzle

Waiting time / Diameter	30	60	120	180	300	400
16	52	41	34	18	18	18
25	80	68	60	45	23	23
30	95	75	64	55	45	28
37	70	64	53	40	35	35
39	65	60	50	40	37	37

Table 3.4 : Vortex Height (mm) for different nozzle diameters (mm

different Waiting times (sec). Mode of filling - Axial

(b) Off-Central Nozzle

W.T. \ Dia	30	37
30	85	57
60	60	50
120	50	45
180	40	40
300	28	35

Table 3.5 : Vortex time (sec) for different nozzle diameters (mm) .
different Waiting times (sec)

a. Mode of Filling - Tangential Centre Position of Nozzl

Waiting time - Diameter	30	60	120	180	300	400	600	900	1200	1500
16	74	94	126	201	230	252	280	300	360	360
25	35	41	53	66	80	86	94	108	132	132
30	28	36	41	47	57	63	69	76	94	100
37	26	30	34	38	42	48	53	58	61	68
39	24	38	31	35	39	44	50	56	59	63

Table 3.5: Vortex Time (sec) for different nozzle diameters (mm)

different Waiting times (sec)

b. Mode of Filling - Tangential Off-Centre Position of Noz

Waiting time - Diameter	30	60	120	300	400	600	900	1200
16	220	244	254	276	360	360	360	360
25	88	84	90	96	100	106	114	132
30	62	57	60	69	74	79	84	98
37	42	38	40	48	53	56	59	68
39	41	35	39	43	47	50	54	63

Table 3.6: Vortex time (sec) for different nozzle diameters (mm
different Waiting times (sec). Mode of filling - Axial

(a) Central Nozzle

Waiting time / Diameter	30	60	120	180	300	480
16	275	290	311	360	360	360
25	95	100	105	110	132	132
30	71	78	81	85	89	98
37	56	58	62	64.5	68	68
39	53	54	58	60	63	63

Table 3.6: Vortex Time (sec) for different nozzle diameters (mm) at dif

Waiting times (sec)

(b) Off-Central Nozzle

W.T. \ Dia.	30	37
30	75	62
60	85	63.5
120	87	65
180	92	68
300	98	68

Table 3.7 : Vortex Height (mm) for different inlet angles (θ) different Waiting times (sec)

a. Nozzle diameter - 30 mm

Inlet angle / Waiting time	0	30	60	90
30	250	18 5	150	9 2
120	200	130	90	64
300	13 7	108	50	45

Table 3.7 : Vortex time (sec) for different inlet angles (θ) a different Waiting times (sec)

b. Nozzle diameter - 30 mm

Inlet angle / Waiting time	0	30	60	90
30	28	44	54	71
120	41	58	72	81
300	51	65	87	89

Table 3.8: Rotational RPM measured at the time of Vortex Formation at 2.5 cm Radius from Centre

Diameter mm / Waiting time (sec)	16 Centric	25 Centric	16 Eccentric
30	63 RPM	64 RPM	60 RPM
120	60 RPM	60 RPM	60 RPM
300	60 RPM	54 RPM	87 RPM

Table 3.9: Measurement of Cyclohexane entrained, as a function of waiting time. 1.5 lit cyclohexane added to the water

Sample No	Water collected	Eutrained Wt. 30 sec	Cyclohexane 120 sec
1	1000 ml	10 ml	10 ml
2	1000 ml	10 ml	10 ml
3	1000 ml	10 ml	10 ml
4	1000 ml	10 ml	9 ml
5	1000 ml	9.2 ml	9 ml

Table 3.10 Influence of slag covers and flow obstacles on vortex hight when water is drained through 30 mm nozzle dia after 120 second waiting time

Nozzle - daimeter : 30 mm

Medium	Vortex hight	Remarks
Pure water drainage	200 mm	-
Drainage in presence of Paraffin oil	191 mm	Suppression of Vortex Formation
Drainage in presence of Paraffin oil	195 mm	Suppression of Vortex Formation
Flow obstacle	160 mm	Suppression of Vortex Formation
Drainage in presence of of thermocole (solid model slag)	No Vortex	Supression of Vortex Formation

Table 3.11 Coefficients obtained from regression analysis for different modes of filling and centre, off-centre position of nozzles

Co-eff / Mode	a_0	a_1	a_2	m	n	A	P	Co-eff of correl.	Sta err cor
Tangential centric	0.213	0.2058	-0.035	-0.55	0.15			0.89	0.
Tangential Eccentric	0.45	0.13	-0.025	-0.56				0.92	0.
Axial centric	-0.369	0.0513	-7.96×10^{-4}	-0.25	0.11			0.90	0
Tangential centric				0.16		2.5	-0.26	0.85	0
Tangential eccentric WT<120				-0.1		0.046	0.685	0.88	0

Table 3.12 : Vortex Predicted for Industrial ladle as a function of waiting time

Waiting Time (min)	Vortex Height (cm)
1	111.366
2	103.9
3	75.0
4	64.0
5	56.6
8	43.5
10	38.0
15	30.0
20	25.9

APPENDIX - A

A control volume is established between reference plane 1, corresponding to the instantaneous liquid level in the vessel, and plane 2 at the discharge end of the nozzle. The energy balance may be written as

$$\frac{\bar{U}_2^2}{2} - \frac{\bar{U}_1^2}{2} + g\left[H_2 - H_1\right] + \frac{P_2 - P_1}{\rho} + F_{fr} = 0 \qquad (1)$$

Selecting the reference level for the potential eneergy so that $H_2 = 0$ and expressing F_{fr} in terms of the friction factor

$$\frac{\bar{U}_2^2}{2} - gH + 2\,f_{fr}^{\,L_n}\,\bar{U}_2^2 \qquad (2)$$

The volumetric flow rate through the nozzle is given as

$$Q_n = \bar{U}_2\,A_n \qquad (3)$$

Relating the rate of change of liquid level to Q

$$A_{vessel}\,\frac{dH}{dt} = Q \qquad (4)$$

Expressing $\bar{U}_2$ interms of other variables

$$\bar{U}_2 = \frac{gH}{\frac{1}{2} + 2f_{fr}\,\frac{L_n}{d_n}} \qquad (5)$$

Boundary condition $H = H_I$ at $t = 0$.

Assuming friction factor independent of the Reynolds number. Time required to empty the vessel becomes

$$t = \frac{d_v^2}{d_n^2}\,\sqrt{(2/g)}\left[1 + 4\,f_{fr}\,\frac{L_n}{d_n}\right]^{1/2}\left[\sqrt{H_I} - \sqrt{H_f}\right]$$